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PROJECT THEMIS

A CENTER FOR THE DESCRIPTION OF ENVIRONMENTAL CONDITIONS WEATHER PHENOMENA

ANNUAL REPORT

By

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December 1970

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OKLAHOMA STATE UNIVERSITY
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A CENTER FOR THE DESCRIPTION

OF ENVIRONMENTAL CONDITIONS

WEATHER PHENOMENA

Third Annual Progress Report
October 1, 1969 through September 30, 1970

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ABSTRACT

The Oklahoma State University Themis Project has developed an algorithm for identifying cloud to ground strokes compared to cloud to cloud strokes. That identification is based upon the relative energies of the strokes in vertical polarization contrasted to horizontal polarization and at the frequencies of 10 KHz, 50 KHz, 150 KHz and 250 KHz.

The project has developed an on-board aircraft analog data reduction package which gives real-time readout of the sferic rate history at any one selected frequency. Close correlation of the sferic rate with vertical cloud development remains the rule and indicates that the sferics are an intimate part of the vertical wind profile.

A CPS-9 weather radar facility has been added to the project and was operated during the 1970 Oklahoma storm season. The first suitable photographs of cloud to ground lightning photographs were obtained late in the spring at Stillwater.

ACKNOWLEDGEMENT

The research work described in this report was sponsored by the Department of Defense under Project Themis. The Oklahoma State University Themis Weather Phenomena research is administere under Contract Number DAAB07-68-C-0083.

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1. INTRODUCTION

A. HISTORY OF PROGRAM

The College of Engineering, Oklahoma State University, submitted Proposal ER 67-T-21 entitled, "A Center for the Description of Environmental Conditions--Weather Phenomena (Themis No. 129)" to the Department of Defense on May 1, 1967, in response to the brochure, Project Themis, dated November, 1966. Authorization to implement the program, with limited funds, was given in the form of a letter contract The effective date of the letter contract was October 1, 1967 The actual contract which authorized the initial three years of the program was signed by the contracting office on January 16, 1968.

On October 30, 1969 the contract between Oklahoma State University and the Department of Defense was amended to authorize full funds for three years - 2/3 funds for one year and 1/3 funds for one year of the contract covering the period October 5, 1969 through October 4, 1972 Word was received during late summer of 1970 that additional funding of this project would not be available. Therefore, the objectives and schedules of the project have not been materially changed from those already set forth.

B OBJECTIVES OF PROGRAM

The proposals submitted have been based on the following objectives:

1. Immediate objective: the determination of the electromagnetic characteristics of severe weather.
2. Intermediate objective: the prediction of operationally restrictive and severe weather.
3. Long-term objective: the modification of operationally restrictive and severe weather.

C. RATIONALE

The recognition and definition of electromagnetic signature associated with specific severe weather occurrences and the development of instrumentation to detect, measure, and analyze the electromagnetic energy present will provide another technique for use in short range weather forecasting. This new method, along with existing meteorological techniques, will be of benefit to the Department of Defense in tactical operations of all the services.

The modification of weather, if possible, will be of benefit to long-range military planning. The ability to either predict or cause a rainstorm, for example in a particular area will provide a tremendous advantage in tactical operations planning.

D. IMPLEMENTATION PLANS

The program was initiated with a three-phased effort;

1. The development and use of instrumentation to measure the electromagnetic signature of certain weather phenomena (clear air turbulance, thunderstorms, tornadoes) in airborne and ground-based laboratories. (The correlation of electromagnetic data to existing meteorological information will be made on identifiable weather phenomena.)
2. The investigation of pattern recognition in the total data acquisition program (sferics, severe weather, existing meteorological information). (The mathematical modeling and information theory application to both the discrete and continuous data will attempt to provide keys for the third phase.)

3. The data analysis and application to identify indicators for probability of specific phenomena, to determine possible trigger mechanisms which induce the phenomena, and to define techniques for possible modification-abatement, diversion or intensification of the phenomena.

4. The development of one or more simple airborne instrument packages which can be put in any aircraft for short term measurement of the severity of weather immediately ahead.

II. DATA GATHERING.

A. CHRONOLOGY OF THE 1970 SEVERE STORM SEASON.

18 April 1970 -- A squall line associated with a cold front formed southeast of Stillwater and spawned a tornado East of Oklahoma City. The CDEC aircraft became airborne following the tornado event.

23 April 1970 -- A stationary front lay east-west across Oklahoma. The storm cells sampled were southeast of Stillwater near Shawnee, Oklahoma. Hail was reported during the sample period.

26 April 1970 -- A dewpoint discontinuity or so called "dry line" existed west and north of Stillwater, Photos were taken from the radar tower but were of poor quality.

10 May 1970 -- A wave formed in the Oklahoma panhandle along a stationary front. Thunderstorms formed along a squall line associated with the low. Hail and possible funnel clouds were reported near Wichita, Kansas during the sample period.

11 May 1970 -- Mild activity west of Stillwater, near Canton Reservoir, continued to be associated with the low center now in Western Kansas and Nebraska.

13 May 1970 -- Agair some activity is associated with the front in Kansas and a dewpoint discontinuity west of Stillwater. The activity moved south of Stillwater into the Tulsa area, but only moderate

thunderstorms resulted.

14 May 1970 -- The front which was stationary in Kansas moved southward as a cold front. Flying was difficult ahead of this system and was terminated as the front passed over Stillwater.

29 May 1970 -- A front lay stationary and to the northwest of Stillwater, Meanwhile, a low was induced in southwestern Oklahoma causing storms near Oklahoma City and Shawnee. A tornado was sighted near Shawnee before the CDEC aircraft began sampling.

9 June 1970 -- A small group of cells formed directly north of Stillwater. Photos were taken from the radar tower at Stillwater and excellent film data was obtained.

10 June 1970 -- A cold front moved rapidly eastward and passed Stillwater in the evening. The CDEC aircraft landed shortly after takeoff due to the impending weather at the airport.

12 June 1970 -- A dewpoint discontinuity lay on tc of Stillwater. Although at 18:30 CDT the sky was cloudless, at 19:00 there was a 45,000' Cb. about ten miles northwest of Stillwater. Later in the storm hail was reported at Ponca City. However, this was a case where few sferics were apparent. Three strokes in all were visible from the ground and the sampling aircraft reported little sferic activity.

In cooperation with the Institute of Atmospheric Sciences at the South Dakota School of Mining & Technology at Rapid City, South Dakota.

6 July 1970 -- Test case @16:43 M.D.T. with Ag I (silver iodide) seeding. Low to occasionally moderate sferics - considered a mild storm.

7 July 70 -- A cold front passed over the area but almost no activity resulted.

9 July 70 -- Test case called @12:05 M.D.T. activity was sudden and sporadic. Considered a mild to moderate storm day with no seeding done.

10 July 70 -- Test case called @13:30 M.D.T. moderate cumulus activity - sferics light. No seeding done.

13 July 70 -- No test cases called due to lack of activity.

In cooperation with the weather modification Branch of the Atmospheric Physics Laboratory at White Sands Missile Range, New Mexico:

23 July 70 -- Hughes and Overton on Organ Peak with WSMR personnel. Light cumulus activity over peak area in afternoon. Some activity at night. Photos were taken but were of poor quality.

24 July 70 -- Pybus and Byrne on Organ Peak. Early evening cell with moderate sferics. Observations from Organ Peak were poor.

27 July 70 -- Observers on the ground. Large area rainstorm northeast of Las Cruces. Moderate sferics with called shots.

28 July 70 -- Several large cells near Truth or Consequences,

New Mexico and north of Deming. Called observations from the airport. These cells showed synchronous sferic activity.

29 July 70 -- One large cell on the Mexican border at Columbus, New Mexico provided a splendid display of various kinds of sferics. Considered the best set of called data yet this season.

In cooperation with the Joint Hail Research Project (JHRP) of the National Center for Atmospheric Research (NCAR), the Colorado State University (CSU), and the University of Wyoming (WU) all operating over the Pawnee Grasslands at Greeley, Colorado and Raymer, Colorado

4 August 70 -- The remnants of a stationary front lay east of the Greeley area. Cells on this day were small, sferics were mild.

5 August 70 -- The old frontal line was near Cheyenne and cells along the line grew moderately strong to produce hail. Sferics were moderate

6 August 70 -- Same line as yesterday's. Cells formed early to the north and moved southward. Hail reported on several occasions.

8 August 70 -- Moderate cell near Julesburg, Colorado produced hail. A later storm directly over Greeley was not sampled.

B. DATA GATHERING - GENERAL SYNOPTIC RESUME.

April 1970 began with a sharp transition from the previous zonal flow to a break up into meridional flow over Oklahoma. A weak trough over the Eastern Rockies (at 700 mb.) brought below normal temperatures and light precipitation to the western half of Oklahoma and above normal temperatures and moderate precipitation to the eastern half of the state.

The trend toward meridional flow continued with weakening of the flow pattern at 700 mb. for both May and June. Temperatures in Oklahoma were near normal in May but went below normal in June. Precipitation remained moderate in May becoming light in June.

The storm season was considered to be a light to moderate one with only a few severe storms. However, those few storms spawned several destructive tornadoes.

July in South Dakota was a light storm season. The zonal flow at 700 mb. was very weak and caused only light precipitation with normal temperatures.

Later that month and into early August a high centered in the southwest dominated the flow at White Sands and at Colorado. Thunderstorms were frequent at those locations, but only moderately severe. No tornadoes were observed at South Dakota, White Sands or Colorado.

III. DATA ANALYSIS.

A. PATTERN RECOGNITION.

1. Introduction:

The progress made in the past year by the Pattern Recognition group is reported in this section. Major efforts in this area have been directed towards developing a mathematical model for lightning discharges, developing a procedure for classifying lightning discharges, developing a statistical model for describing thunderstorm noise and theoretical investigation of the problem of learning to recognize patterns with an imperfect teacher. These efforts have resulted in three doctoral dissertations and four technical papers that are being submitted for publication in research journals:

Ph.D. Dissertations:

1) "Learning to Recognize Patterns With an Imperfect Teacher", by K. Shanmugam, completed in May, 1970
2) "A Study of the Second-Order Statistical Properties of Thunderstorm Noise", by Richard L. Johnson, completed in September, 1970.
3) "A Lightning Model for Pattern Recognition", by Guy O. Marney, completed in November, 1970.

Technical Papers:

1) "Learning With an Imperfect Teacher", by K. Shanmugam and A. M. Breipohl, Proceedings of the 1970 IEEE SSC Conference, pp. 32-38, Pittsburg, October 14-16, 1970.
2) "An Error Correcting Scheme for Learning With an Imperfect Teacher", by K. Shanmugam and A. M. Breipohl, accepted for publication by the IEEE transactions on Systems Science and Cybernetics.

3) "Discriminating Between Cloud to Ground and Cloud to Cloud Lightning Discharges, A Pattern Recognition Approach", by K. Shanmugam and A. M. Breipohl, accepted for publication in the Journal of Geophysical Research.

4) "A Study of the Second Order Statistical Properties of Thunder Storm Noise", by R. L. Johnson, being submitted to the Journal of Geophysical Research.

A brief summary of the above listed works will be presented in the following sections. For a detailed description, the interested reader is referred to Appendix A of this report, which contains abstracts of the listed dissertations and copies of the listed papers.

2. Modeling of Lightning Discharges:

The objective of this phase of research is to develop a Fortran program to implement a mathematical model of a lightning discharge of a given geometry on the digital computer. The general geometry of the discharge model, illustrated in Figure 1, consists of straight segments connecting points A and B, with branching segments extending from B. At this time, TOL, a time-varying current IL(t)

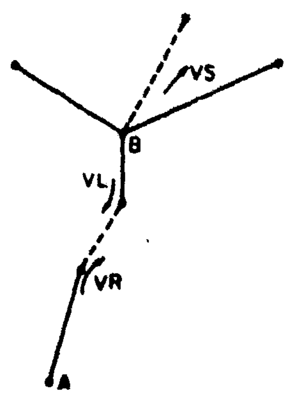


Figure 1. General Geometry of Discharge Model

is allowed to progress down the main channel from B to A with a velocity VL(t) which may be of the form $VL(t) = VL_0 EXP(-GLt)$. At a later time TOR a return current IR(t) is allowed to move up the channel from A to B with a velocity VR(t). Still later in time, TOS, a third current IS(t) moves from B towards the branch tips with a velocity VS(t). The programs calculate the electromagnetic fields at any specified observation point by approximating each straight segment by a prescribed number of oscillating electric dipoles.

One program calculates the Fourier transform of the fields resulting from the above model. The other, which is essentially an extension of the first program, calculates the comb-filter outputs that would result from the assumed discharge model.

At present only the return storke is being investigated (IL(t) = IS(t) = 0) for comparison with models existing in the literature. This requires that the channel between A and B be represented by a vertical segment and the observation point be located on the earth's surface 100 Km. from the channel.

An accepted waveform for the return stroke current is

$$IR(t) = I_0 (e^{-\alpha t} - e^{-\beta t}) + I_1 e^{-\gamma t}.$$

A standard velocity expression is

$$VR(t) = VR_0 e^{-GRt}.$$

Typical values for a first return stroke in a discharge are: $I = 3 \times 10^4$ amp., $I_1 = 2.5 \times 10^3$ amp., $\alpha = 2 \times 10^4$ sec.$^{-1}$, $\beta = 2 \times 10^5$ sec.$^{-1}$, $\gamma = 10^3$ sec.$^{-1}$, $VR_0 = 8 \times 10^7$ m/sec., $FR = 3 \times 10^4$ sec.$^{-1}$.

The maximum channel height allowed by the expression VR(t) is VR_0/GR or $2\frac{2}{3}$ Km. for the constants given. Using the above current and velocity expressions, Figure 2 illustrates the magnitude of the Fourier transform of the vertical field at 100 Km. on the earth's surface for a 2.66 Km. vertical discharge approximated by 266 10 m. dipoles. This graph is in agreement with that found in the literature (1, 2).

If GR is set equal to zero, VR(t) = 8×10^7 m./sec and the length of the channel may be as long as desired. At the present time it is only noted that increasing the channel height reduces the frequency at which the main peak of the Fourier transform occurs, and this shifting on the frequency axis may be some indication of storm height.

This model is now being extended to include stepped leaders. Also modeling of cloud to cloud discharges will be attempted. The result of this study will be reported in a doctoral dissertation expected to be completed in November, 1970.

3 Classification of Lightning Discharges:

In this phase of the project a procedure has been developed for classifying lightning discharges into cloud to ground or cloud to cloud type based on sferic data. Using this procedure we hope to study the changes in the lightning structure of the storm in relation to the severe storm events occurring in the storm.

All the data used in this phase of the project were taken from the narrow-band recordings of the various comb-filter outputs. The edge tracks of the narrow-band recordings contain descriptions about the types of discharges that were visible to the observer in the aircraft. Sections of narrow-band data containing identified

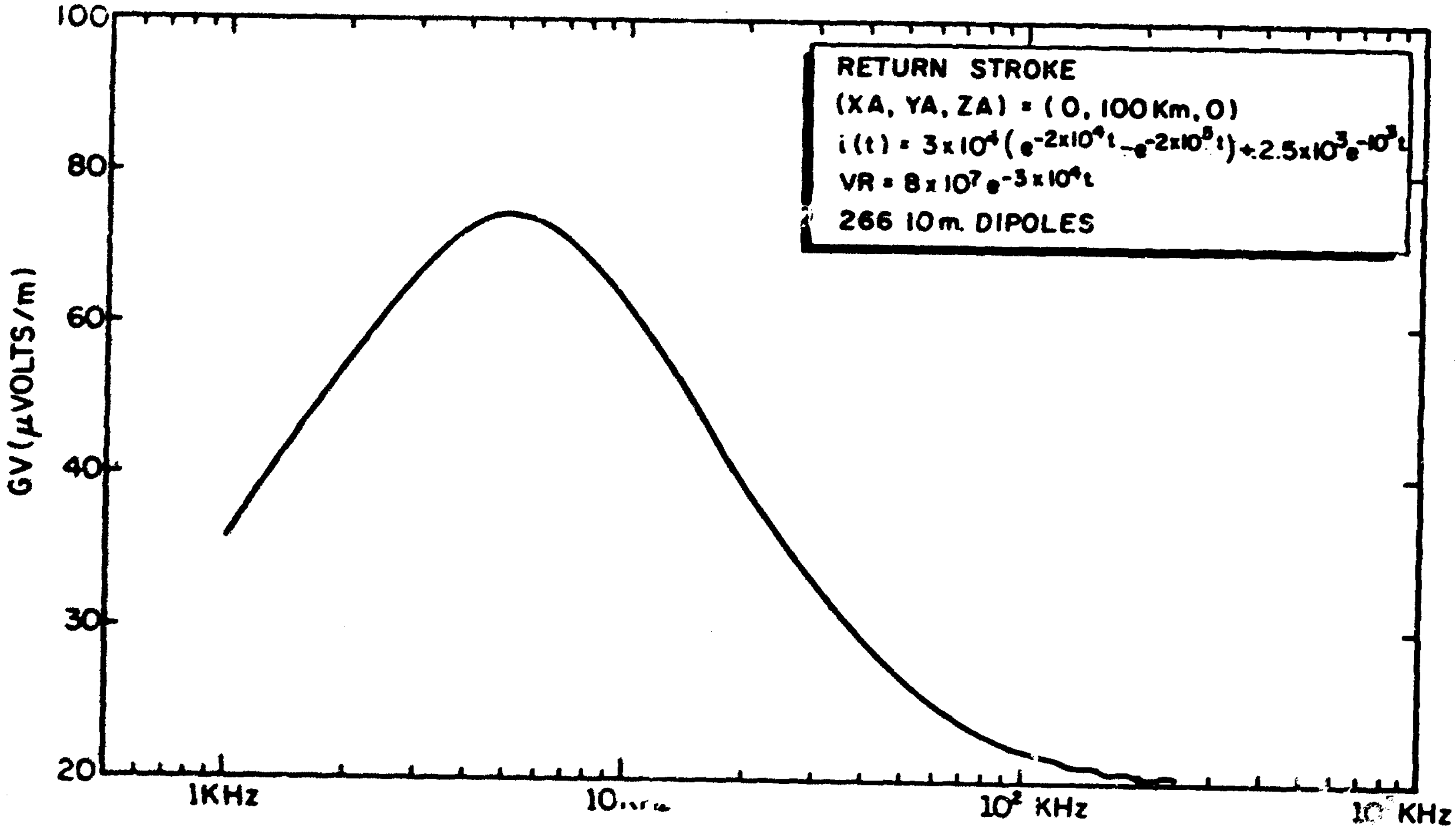


Figure 2. 2.66 Km. Return St:oke

discharges were selected and the data were digitized on eight channels (10KHz, 50KHz, 150KHz, 250KHz horizontal and vertical). From these data, a set of measurements representative of the relative amounts of energy in various comb-filter frequencies was computed. These measurements consist of the normalized average value of the signal in each comb-filter channel. The average value of the signal in each horizontal channel ($\overline{X}_{10H}$, $\overline{X}_{50H}$, $\overline{X}_{150H}$, $\overline{X}_{250H}$) were normalized with respect to the sum of averages in the four horizontal channels ($\overline{X}_{H}$). Similarly the average values in the vertical channels ($\overline{X}_{10V}$, $\overline{X}_{50V}$, $\overline{X}_{150V}$, $\overline{X}_{250V}$) were normalized with respect to the sum of the averages in the four vertical channels ($\overline{X}_{V}$). In addition to these measurements, the sum of averages in the horizontal channels ($\overline{X}_{V}$) normalized with respect to the total sum were also included to provide some information about the polarization of the received signal. This is the basic set of measurements used in this investigation.

The narrow-band data corresponding to a total of 86 discharges have been processed for these measurements. The following conclusions are drawn from the study of these 86 sample patterns:

1) Cloud to ground discharges have more energy in 10KHz Horizontal than in 50KHz Horizontal. In comparison, cloud to cloud discharges have more energy in 50 KHz Horizontal.
2) Cloud to cloud discharges have more horizontally polarized energy than cloud to ground discharges.
3) There is significant difference in the polarization of cloud to ground and cloud to cloud discharges in 50KHz range.

Using these 86 sample patterns, a computer was "trained" to classify discharges into cloud to ground or cloud to cloud types using three different methods. Using a "test set" of 50 discharges of known types, the performance of the classification scheme was evaluated. It was found that the procedures developed can be used to classify discharges with a reliability of up to 82%.

For details of this phase of the project, the interested reader is referred to the paper "Discriminating Between Cloud to Ground and Cloud to Cloud Discharges: A Pattern Recognition Approach", enclosed in Appendix A of this report.

4. Statistical Model for Thunderstorm Noise:

A study of the second order statistical properties of thunderstorm noise was undertaken in this phase of the project. A characterization of thunderstorm noise was obtained in terms of the time averaged autocorrelation and power spectral density functions. The data was first analyzed to determine whether or not a stationary assumption would be valid. It was found that the sferic triggering mechanism can be modeled by a Poisson impulse process. Based on this property of wide sense stationarity, estimates of the averaged autocorrelation and power spectral density functions were computed from three data segments of 0.75 second duration. Because of close resemblance of the three estimates, the mean of the time averaged autocorrelation and power spectral density estimates is believed to be a reasonable description of the process. This representation is useful in the design of filters for the purpose of minimizing thunderstorm noise inference in a mean square sense.

Details of this study and the results can be found in the paper

"A Study of the Second Order Statistical Properties of Thunderstorm Noise" included in this report.

5. Theoretical Research in Pattern Recognition:

In problems involving learning to recognize patterns, a set of sample patterns with known identifications is necessary. For example in classifying lightning discharges, data from a set of discharges along with the type of discharge from which these data came from is required to train a computer.

Usually a sample identification scheme furnishes the identification for the sample patterns. In many practical situations the sample identification scheme may incorrectly identify some of the training samples. For example in attempts to classify severe storm patterns using electromagnetic data from the storms, meteorological measurements such as reports of hail will be used as standards for identifying the sample patterns. Often these measurements such as reports of hail are unreliable and hence there is a possibility of some incorrectly identified sample patterns. Another example where there is a possibility of incorrect identification of sample patterns occurs in attempts to classify lightning discharges into cloud to cloud or cloud to ground type based on electromagnetic data. Here the sample identification is based on visual sightings of the discharges. In many occasions, the discharge is only partly visible and hence the possibility of incorrect identification. These examples give the motivation for investigating pattern recognition schemes where the teacher, or the sample identification scheme, is known to be imperfect.

This investigation resulted in the development of a nonparametric

scheme for learning to recognize patterns with an imperfect teacher. Under certain mild assumptions on the probabilistic structure of the patterns, it was found that the proposed learning scheme asymptotically bettered the performance of its own teacher. Taking this as a motivation, the proposed learning scheme was modified to correct the errors made by the imperfect teacher. This error correction scheme was found to improve the performance of the learning scheme. Details of this investigation can be found in two papers:

1) "Learning With an Imperfect Teacher"

2) "An Error Correcting Scheme for Learning With an Imperfect Teacher"

enclosed in Appendix A of this report.

The procedures developed for learning to recognize patterns involve the estimation of probability density functions. One way of estimating these density functions is in the form of a polynomial, whose coefficients can be updated recursively. Two problems encountered here are 1) determining how many terms should be included in the polynomial and 2) how many sample patterns are needed to get a given degree of accuracy.

Bounds on the sample size required to insure a desired degree of precision on the estimates have been obtained. Further research is needed to determine the number of terms that should be included in the polynomial.

6. Outline of Research for the Coming Year:

The pattern recognition scheme for classifying lightning discharges has shown that there is enough information in the narrow band data to discriminate between the different types of discharges.

Attempts will be made in the coming year towards relating changes in meteorological conditions of the storms to changes in the lightning structure of the storm. The meteorological conditions of the storms occurring in Oklahoma will be processed from the NSSL radar data. Accordingly the electromagnetic data from storms in Oklahoma will be analyzed first.

Studies on sferic count of narrow band data will be continued. Also studies will be made on the changes in polarization of the narrow band signal.

B. ANALOG DATA REDUCTION.

A scheme was devised and reported upon last year for using analog methods of data reduction to produce a storm's sferic-rate history. Since that time two developments have taken place. First, the data so obtained have been correlated with the storm meteorology and two cases of significance are shown here below. Second, a portable unit was installed in the CDEC sampling aircraft and enabled sferic-rates to be observed during real-time, i.e. during flight. The capability was first operational during August 1970 and will be shown below.

1. Sferic Rate History Correlations.

Following are excerpts from a paper presented by title at the A.M.S. Cloud Physics Conference at Fort Collins, Colorado, on 27 August 1970 and also presented and discussed at the 14th Radar Meteorology Conference in Tucson, Arizona on 19 November 1970.

Sferic Rate Calculations

To obtain sferic rate history for a storm, the procedure used is to choose one of the six frequencies of a vertical antenna system and count the number of lightning strokes using a running weighted average technique.

Analytically, each count is diminished in time (i.e. in weight) by a factor (1-1/e) in one minute, i.e. time constant = τ = 60 sec for (1-1/e)X count. Electrically this is accomplished in real time by providing an RC time constant of one minute across an integrating operational amplifier.

Figure 3 shows the schematic of the data reduction procedure. In brief, the sferic signal from one trace of the taped data is A) amplified B) counted C) integrated D) recorded. Figure 4 shows

a typical record of such sferic rate histories at five frequencies, in this case for the storm at Rapid City, South Dakota, on 14 July 1969 (vertically polarized).

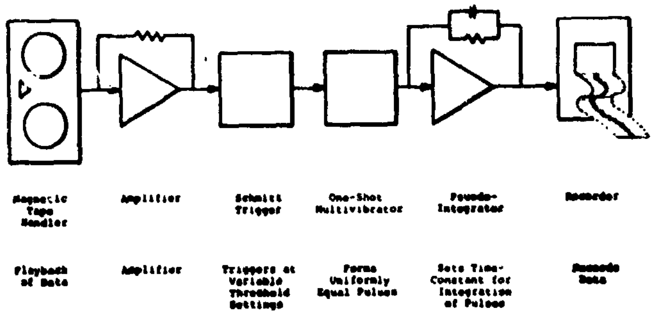


Figure 3. Schematic of Analog Data Reduction

Storm Cases

It is observed in the data to be presented here that A) sferic rates increase with increased vertical cloud building and B) sferic rates increase at the time of individual severe storm events such as hail and tornadoes. The implication is that hail and tornado events occur at the time of rapid vertical cloud development.

Each of two storm cases will be examined by itself in the following paragraphs.

a. 17 July 1969 - Rapid City, South Dakota

Four sources of information were used to analyze this storm: 1) O.S.U. sferic records obtained by the aircraft sferic data sampling system described earlier; 2) Institute of Atmospheric Sciences radar cloud profile records obtained with I.A.S. radar facility at Rapid City; 3) Recorded radio comments giving events and location of events such as hail and tornadoes; 4) O.S.U. observer's flight

log of meteorological events during the course of the flight.

Figure 4 presents the sferic rate history for five discrete frequencies recorded through the vertically polarized receiver and comb filter system described earlier (Section I).

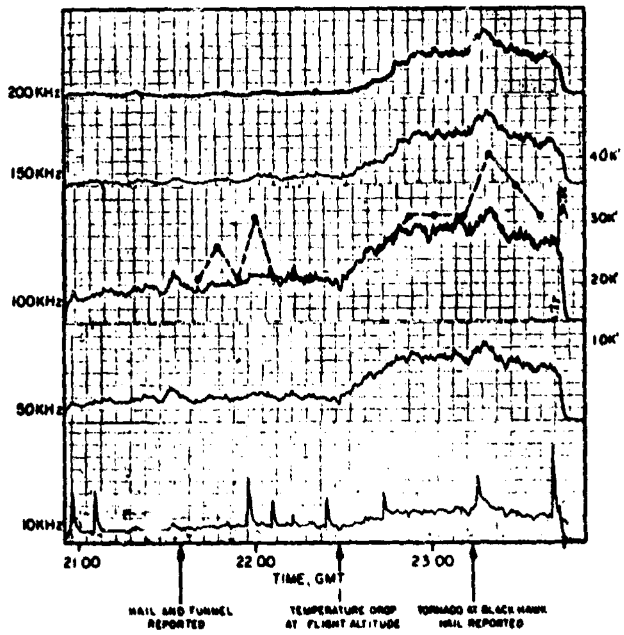


Figure 4. Sferic rate history, storm of 17 July 1969, Rapid City, South Dakota

Figure 4 also presents the I.A.S. radar data plotted on the 100 KHz data, in the form of maximum cloud heights, for the significant cells being sampled. A note of explanation is in order concerning the location of the significant cells.

A forecast is made by the I.A.S. Meteorologist as to the grid squares (of a previously determined grid network) where severe weather is likely to occur. Those forecast grid squares are then sampled by the radar to record existing conditions. The forecasts

are made for approximately half hour intervals in advance.

Occasionally it happens that the major storm activity does not coincide with the grid squares being sampled by the radar. That is, there may be more intense storm activity outside the grid squares being sampled than in those squares. However, that was not the case on this storm of 17 July 1969. Major storm activity was contained within the designated grid squares.

At the bottom of Figure 4 are noted the events recorded on magnetic tape during the storm as well as pertinent notes from the observer's flight log as seen from the 16,500 foot flight altitude.

It is quite clear from the comparison of the data of Figure 4 that cloud building in the early part of the storm, i.e. about 21:30 GMT was not accompanied by much sferic activity. Visual observations show that that part of the storm did not develop to any great extent. Notice, however, that hail and a vortex (not reaching ground) were generated by that time (21:35 GMT).

In contrast, note the increased sferic rate at 22:40 GMT which was accompanied by cloud tops growing above the 30,000 foot height. Hail and a tornado on the ground near Black Hawk, South Dakota were noted during this later cloud building.

It seems almost too coincidental to ignore the slight but unquestionable small-scale increases of sferics at the same times that funnel clouds and hail occur. However, there appear to be other minor increases of sferic rate without those events being observed.

b. 11 June 1969 - Stillwater, Oklahoma

Three sources of information were used to analyze this storm:

1) O.S.U. sferic records obtained by the aircraft sferic data sampling system, 2) National Severe Storms Laboratory (hereafter designated NSSL), Norman, Oklahoma, radar cloud height information, and 3) recorded radio comments concerning the storm and aircraft locations.

Figure 5 presents the sferic rate history at the six discrete frequencies for this storm, as recorded on the vertically polarized receiving system of the sampling aircraft. The aircraft was generally located east of the line of storm cells and was west of Oklahoma City when a tornado was reported near Fairview, Oklahoma, northwest of Oklahoma City.

Superimposed upon the plot of Figure 5 are the three available cloud top height reports of the NSSL radar.

The first event of interest during this storm of 11 June 1969 was a tornado near Fairview, Oklahoma. Time of occurrence of the tornado was 03:10 GMT as can best be determined from ground reports. However, it was probably associated with the very pronounced sferic peak at 03:08 GMT. That impulse of sferic activity (peak at 03:08 GMT) shows a rapid increase of sferic rate. Past experience leads one to suspect a sizeable updraft velocity existed.

The second event of interest during this storm resulted from NSSL radar information subsequent to the tornado event Three cloud height reports are shown plotted with respect to the received sferic rate. One can only say that cloud tops seen by radar appear to correlate well with the sferic rate of the storm, as was the case in the South Dakota storm of part A. Note here, however, the abrupt decrease in sferics as the storm"topped out", i.e., ceased to grow.

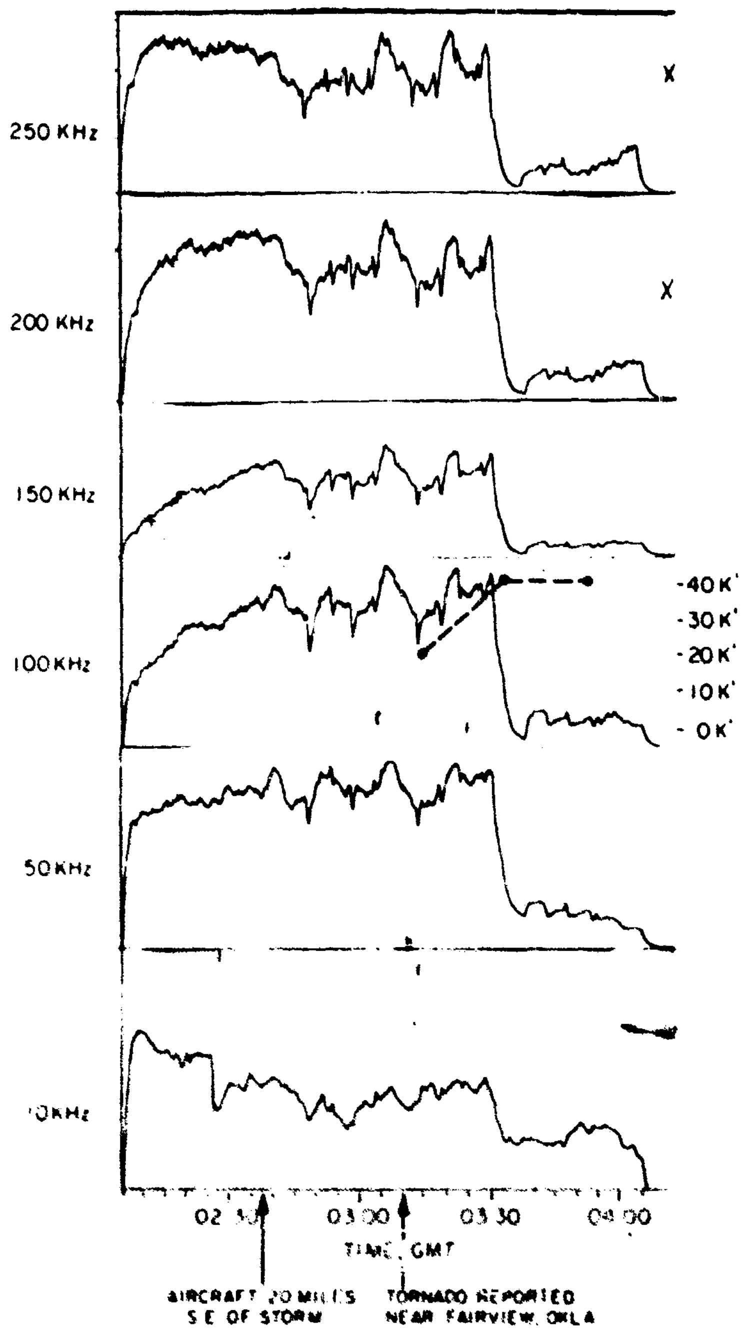


Figure [illegible].

Sferic Rate History for Storm of
11 June 1969, near Fairview, Oklahoma

The data remain suspect at the time, although there is no malfunction nor other abnormal condition that can be found during data gathering and during data reduction. If true, these data show a storm which almost literally blew itself apart.

Conclusions

The two well defined storm cases presented here show a correlation between rapid cloud growth and sferic rate. Other cases, not presented here, give examples of similar correlation. However, there are also cases of rapid visible and radar reported cloud growths not accompanied by the increase in sferic rate. Therefore, we must conclude that a rapid increase in sferic rate signals rapid cloud building, but rapid cloud building may also occur without a significant sferic rate increase.

It is also concluded that more meteorology must be in hand to determine why some storms are more electrically active than others. Nuclei and cloud particle concentrations must be known as well as freezing levels and temperature structure of the storms.

Further analysis of these and other storms is being done to quantify the sferic rate and updraft velocity. The data shown here are sufficient only to indicate what might be a reasonable correlation. This lead must now be followed by stronger and quantitative proof of the stated correlation.

2. CDEC Results From The Colorado Joint Hail Research Project (JHPP).

The airborne sferic-rate recorder is a solid state version of the laboratory device and differs only in the options allowed to change preamplifier gains and integration time constants.

The airborne device was installed during the latter part of

July and tested during the CDEC field trip to WSMR, New Mexico. However, the system was not considered operational until the August 1970 CDEC field trip to Greeley, Colorado, in conjuntion with the joint Hail Research Project. The following data was obtained during that data gathering trip.

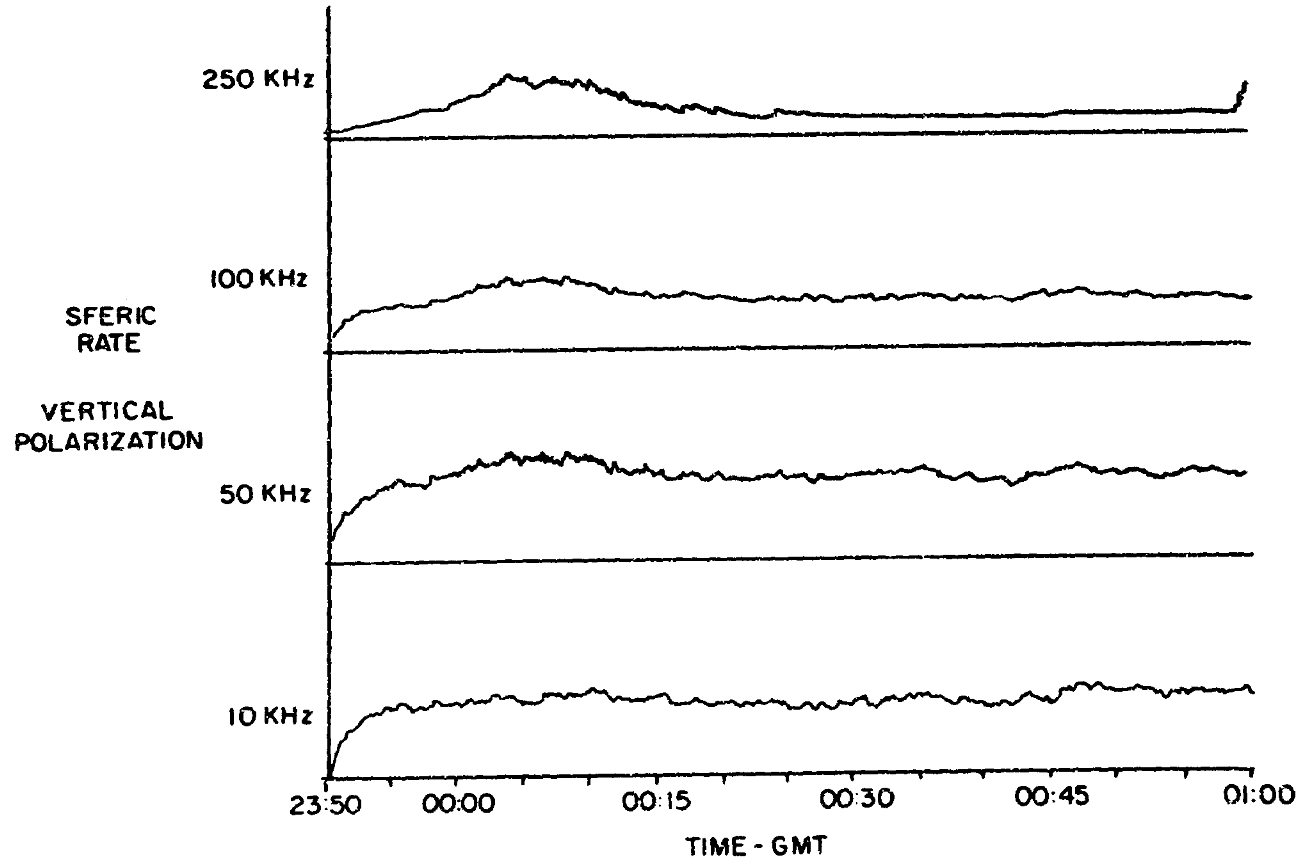
a. August 4, 1970 - Greeley, Colorado with JHRP

Figure 6 shows a sferic rate history at four frequencies for a small storm which failed to intensify on 4 August 1970. The time of occurrence of the main shower activity coincides with the maximum of sferic rate at 00:05 GMT and is most readily apparent on the 250 KHz trace.

b. August 5, 1970 - Greeley, Colorado with JHRP

There existed a line of storm development from northeast of Cheyenne, Wyoming, to northeast of Greeley, Colorado. Development of activity was from the northern end (Cheyenne) southward. The initial buildups were mostly rainshowers of considerable duration and magnitude. However the main storm developed east of Greely and became a cumulonimbus with hailstorm later in the afternoon.

The sferic record, Figure 7, shows several unexplained phenomena in the sferic rate as well as more common features. The abrupt peaks in the 10 KHz trace at 21:12, 21:32 and peaks near 21:45 GMT can not yet be explained. The decrease in sferic rate shown at 20:50 at 50 KHz, 100 KHz and 250 KHz is the decay of a large cell located near Cheyenne. Brief buildups in intensity on the south end of the storm line, i.e. between Cheyenne and Grover, Colorado show at 21:12 and at 21:37. A subsequent buildup at 22:05 continued to develop into a hailstorm with hail reported about 22:30 GMT.



JOINT HAIL RESEARCH PROJECT
GREELEY, COLORADO
4 AUGUST 1970

Figure 6.

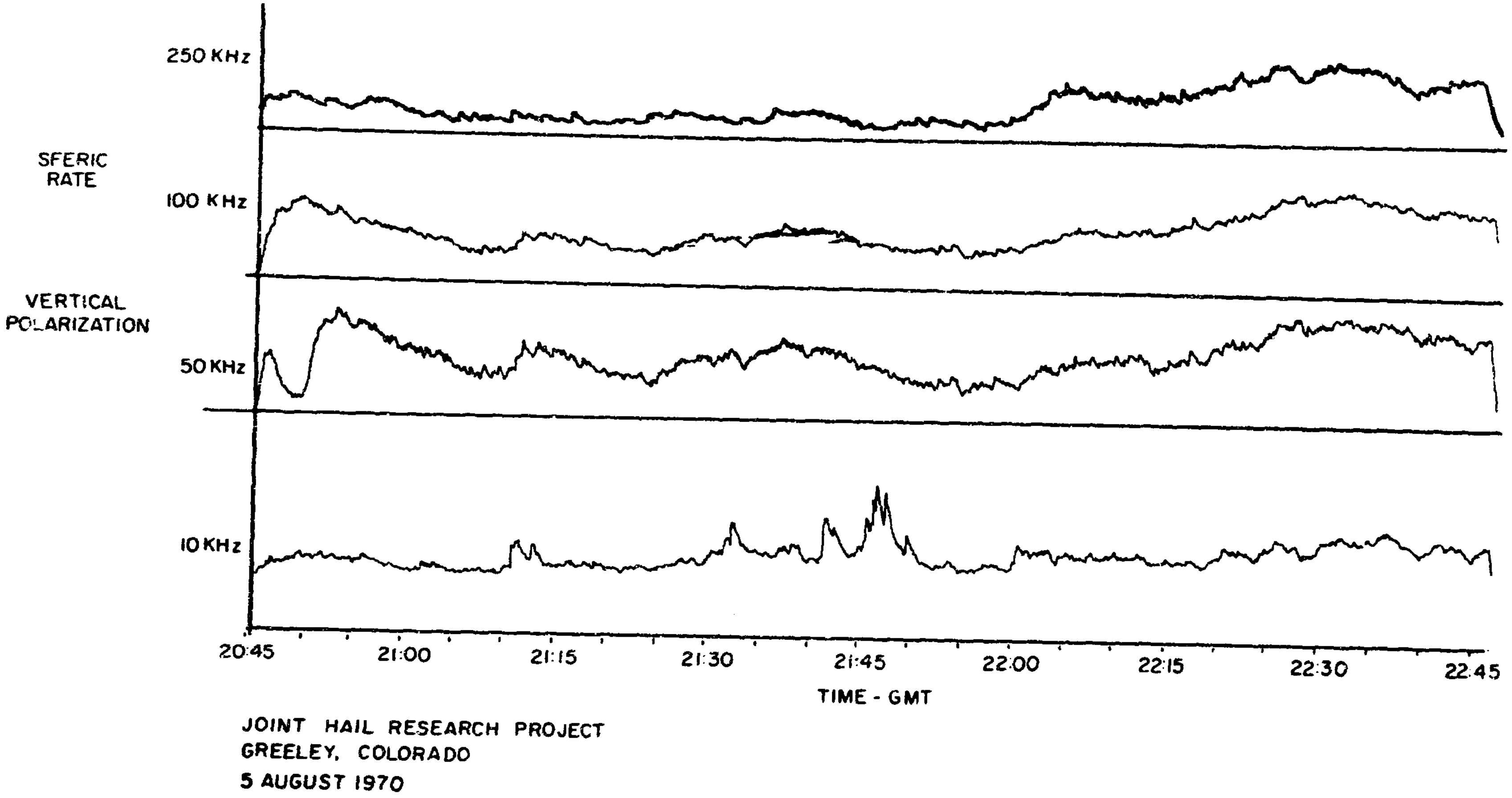

250 KHz
SFERIC RATE
100 KHz
VERTICAL POLARIZATION
50 KHz
10 KHz
20:45
21:00
21:15
21:30
21:45
22:00
22:15
22:30
22:45
TIME - GMT
JOINT HAIL RESEARCH PROJECT
GREELEY, COLORADO
5 AUGUST 1970

Figure 7.

The brief drop in sferic rate at 20:50 on the 50 KHz trace is an anomaly which can not be explained at this time. The period between growth impulses on this storm is taken to be about 25 minutes.

c. August 6, 1970 - Greely, Colorado with JHRP

The situation on August 6, 1970, was similar to that of August 5th. A line of activity extended from east of Cheyenne, Wyoming southward to east of Greeley, Colorado with the northern part of the line developing early storms and subsequent development southward. However, the storm cells on August 6 developed earlier and contained hail earlier than on the previous day. The periods of development, i.e. the growth impulses, show clearly at 250 KHz in Figure 8. 20:15 GMT shows the first of a series of significant growth impulses. The period between impulses for this storm was ten minutes. Hail to 1 1/2" was reported from the later parts of the storm.

3. Conclusions from the Data

From the data shown here and in previous reports it is evident that the sferic rate is intimately related to the vertical development of a thunderstorm. Furthermore, the spacing of growth impulses during any one storm seems to be regular and fairly constant on any one day. The growth impulses on August 5 did not vary from 25 minutes by more than seven minutes. Those on August 6 did not vary from ten minutes by more than two minutes. There were standard deviations of .6 and .35 respectively for the periods between impulses of the two storms. Those small deviations seem to be the general rule . the storms so far examined by the use of sferics.

10KHz sferics seem to correspond more closely to the general

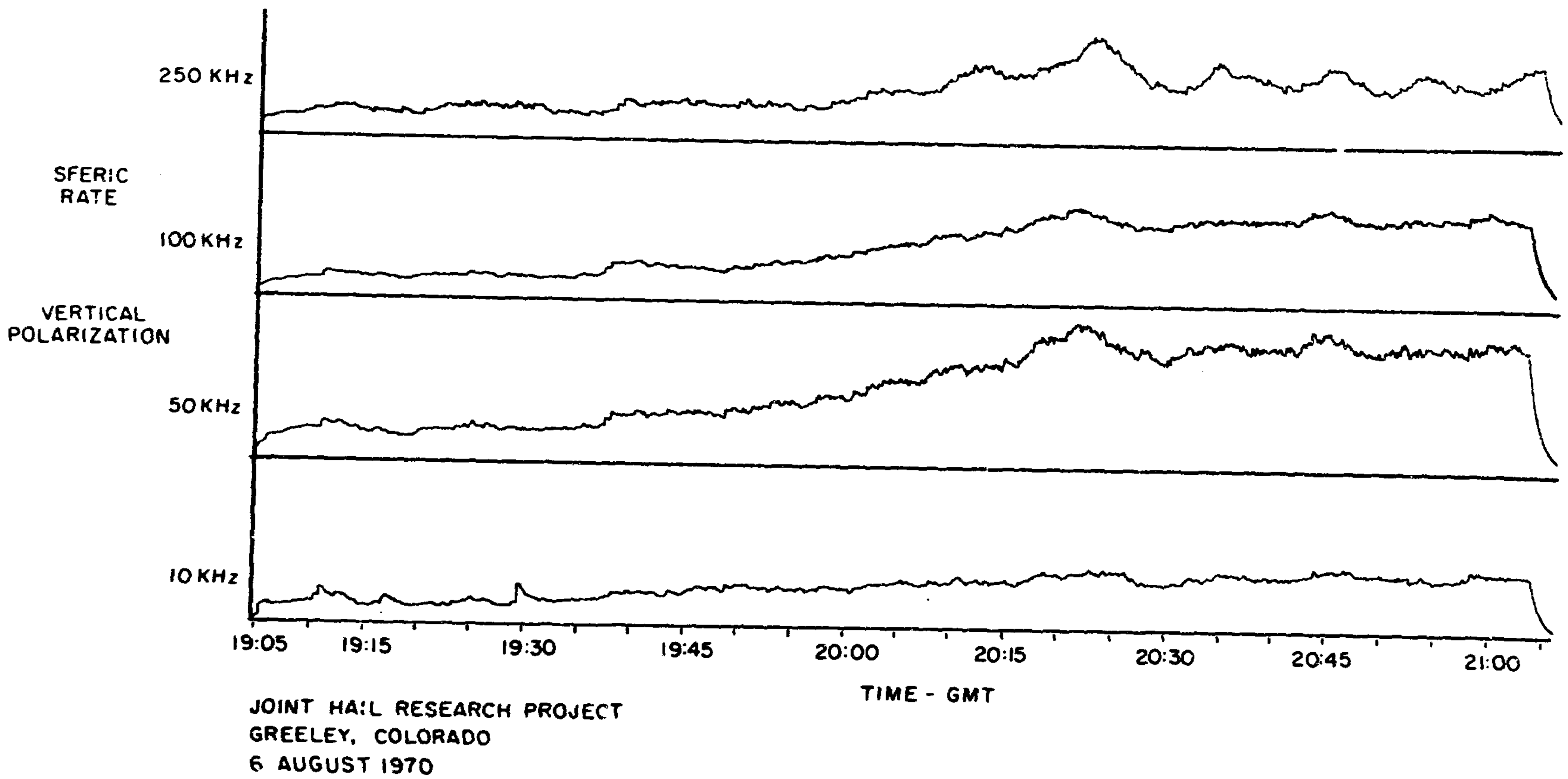

250 KHz
SFERIC RATE
100 KHz
VERTICAL POLARIZATION
50 KHz
10 KHz
19:05
19:15
19:30
19:45
20:00
20:15
20:30
20:45
21:00
TIME - GMT
JOINT HAIL RESEARCH PROJECT
GREELEY, COLORADO
6 AUGUST 1970

Figure 8.

area activity rather than to the activity in a particular cell. The higher frequencies, expecially 250 KHz, provide the most sensitive indicator of local cell development

IV. DATA PROCESSING EQUIPMENT, PROGRAMS AND PROCEDURES.

During the period covered by this report, a number of new digital programs and procedures were developed. Additionally, a 12-channel multiplexer was designed and constructed as was a sferic activity meter.

For the benefit of project members, as a reference and guide, some of the earlier developed programs will be included herein in order that a complete package will be available. These older programs are named ADC1, ADC2 and ADC3.

Much of the data processing work associated with the project hinges around the procedure of playing back analog data tapes, converting th data to digital form-on tape-and then doing the main computation on an IBM 360/65 computer.

The experience with this procedure thus far has shown that nothing can be left to chance in the process. To insure the integrity of the data at each step, the procedure and results must be checked and re-checked.

The analog data tape is 1 inch tape recorded with a total of fourteen channels. When desired twelve, or fewer, of these channels may be digitized through the use of the multiplexer. When digitizing only one channel the conversion rate can be as high as 24,000 samples per second.

The resulting digital tape is standard 9-track IBM standard. If the digital data tape was being created on the IBM 360 computing system, then either IBM labelled or unlabelled tapes could be created easily. However, when the data is being written on the tape by another processor (HP2115A), as is being done on the subject project, then in order that these tapes can be read back by the IBM 360/65, certain preparations must be observed. If the digitized data is to be written onto an

unlabelled tape, then the HP2115A program need only to write a tape-mark (end-of-file) prior to the first data set. While unlabelled tapes are somewhat easier to create, there is a danger that a tape with good data on it be inadvertently used improperly on the 360/65.

The use of labelled tapes circumvents the problem of tapes being used improperly; however, creating a labelled tape is a more involved procedure. First, the reel of tape must be submitted to the 360/65 facility as a special run solely for the purpose of putting a unique label on the tape. At this time, the user specified the volume and serial name to be used. After the tape is returned, the user will need to load a data set name on the tape. This may be accomplished by running a normal FORTRAN job-with dummy data-to place a data set on the tape. This will complete the standard label such that it will be read properly by FORTRAN in the future. When the blank labelled tape is loaded on the HP2115A system to receive digitized data, the HP2115A program must initially cause the first four records to be skipped. Then the data is written. These four records constitute the label.

PROGRAMS

The program entitled ADC1 and listed as Figure B-1, is for the purpose of converting data at speeds up to 24,000 samples per second and writing the result on an unlabelled digital tape The digital data is in raw binary form. A program is available for the IBM 360/65 computer for converting this data to 32-bit floating-point form compatible to FORTRAN IV (360).

ADC2 given in Figure B-2 is also for converting data at speeds up to 24,000 SPS. Only one record is converted at a time, and some flexibility

in use is provided. The procedure is included as part of Figure B-2.

ADC2A presented in Figure B-3is similar to ADC2 except that a labelled tape is used and the digitized data is written on the tape directly in 32-bit floating point form ready to be read by 360 FORTRAN IV. This necessitates a maximum convert rate of 13,000 SPS.

ADC3, Figure B-4, can be used for reading a record of data from the digital tape back into the processor. This is for the purpose of checking the nature of the data on a digital tape.

ADC4 depicted in Figure B-5, is similar to ADC1. Data is converted continuously for a specified number of records and written on a standard labelled tape in 32-bit floating point form. This limits the maximum sampling to 13,000 SPS but the output tapes are ready to be read by a 360/65 FORTRAN IV program.

ADC5 shown as Figure B-6, is the same as ADC4 except it outputs on an unlabelled tape.

DIAG1, Figure B-7, is designed to transfer data from the analog-to-digital converter into the B-register of the HP2115A processor. This is for the purpose of checking for proper operation of the A/D converter and the I/O interface.

DIAG2, Figure B-8, is a magnetic tape reading program. It allows the operator to go forward or backwards on the tape in steps of records. Data on any record may be observed and tape marks are clearly indicated.

DIAG3 of Figure B-9, consists of two independent programs. These are for testing and adjusting the multiplexer.

ADC1 Program

Purpose: To digitize analog data continuously.

Speed: Up to 24,000 samples per second.

Output tape: Unlabelled 9-track. Data in raw 16 bit binary form. $2{,}000_{10}$ words per record. (This number can be changed.) Mount tape.

Procedure: Load program using HP2115A Basic Binary Loader. (BBL) Program origin is at 100 octal.

Halt No. 1 - Load switches with number of records to be written. (octal) Push run.

Halt No. 2 - Wait to ready the system. Push run to start system.

Halt No. 3 - Records complete. Push run to write EOF and rewind tape.

Halt No. 4 - End. Mount another tape, push run to repeat entire program.

ADC2 Program

Purpose: To digitize one record at a ime.

Speed: Up to 24,000 samples per second.

Output tape: Unlabelled 9-track. Data in raw 16-bit binary form. 2048_{10} words per record. This can be changed.

Special: Forward spacing of records can be accomplished, so a tape may be taken down and then remounted later and continued.

Procedure: Mount tape
Load program tape using BBL.
Program entry is 100 octal. Push run.
Halt No. 1 - Set Switches to the number of records to be skipped. Push run.
Halt No. 2 - Waiting. Push run to convert.
Halt No. 3 - Set Switches one of three options. Then push run.

000 - To convert another record. Goes back to Halt No. 2.

001 - Backspace one record. Push run Goes back to Halt No. 2.

010 - Rewinds tape. Push run. There is no EOF mark.

Halt after rewind is end.
Branch manually to address 100 (octal) to repeat, if desired.

ADC2A Program

Purpose: To digitize one or more records at a time.

Speed: Up to 13,000 samples per second.

Output tape: Labelled 9-track. Data is in 32-bit 360/65 floating point form. 1944 words per record (can be changed).

Procedure: Mount a labelled tape.
Load program using the BBL.
Program entry is 100 octal. Do not push run yet.
If it is desired to space forward on tape then turn on bit switch 15. Then push run.
Otherwise, push run.
Halt 14 - Load switches with number of records to be skipped. Push run.
Halt Ø - Enter number of records desired into switch register. Push run.
Halt 1 - Program ready and waiting to start converting data. Push run to start.
Halt 66 - A data convert run is finished.

(a) To proceed with another run, turn on bit switch Ø and push run. The program will return to Halt Ø. Turn off SW Ø.

(b) To backspace a desired number of records, set bit SW 15 and push run. Program will backspace the tape and then return to Halt Ø. Turn off SW 15.

Halt 6 and 7 - Error halts. Clock rate too fast
Halt 25 - Tape not accepted (not proper label).

ADC3 Program

Purpose: To read a digital tape record in HP2115A memory.

Features: Can Forward space past records. Examine words in a record using front panel lights.

Procedure: Mount tape.
Load program with BBL
Program entry is 16100 octal. Push run.
Halt No. 1 - Load switch register with number of records to be skipped. Push run.
Halt No. 2 - Ready to read tape.
Push run to read.
Returns to Halt No. 1.
Data may be viewed on T-register lights.

Tape data is loaded into memory address 02000 octal.
2048 words per record (can be changed).

Halt No. 1 - If desired to rewind tape - set bit SW 15, push run.

ADC4 Program

Purpose: To digitize analog data continuously

Speed: Up to 13,000 samples per second.

Output Tape: Labelled 9-track. Data is in 32-bit floating point form.
1944 words per record (can be changed).
Can have multiple files (data sets).

Procedure: Mount tape.
Load program with BBL.
Entry address is 100 octal. Push run.
Halt Ø - Enter number of records to be written in switch register. Octal. Push run.
Halt 1 - Ready to convert. Push run to start converting
Halt 66 and Halt 77 - Normal end. Data loaded. Push run to write EOF. Then stops on Halt 70
Halt 70 - Push run sends program back to Halt Ø for a second file (data set).
If set SW15, then push run, a second EOF is written (End of volume).
Tape is rewound-stops on Halt 65 or Halt 76.
Halt 6 and Halt 7 - Error halts. Slow clock rate

ADC5 Program

Purpose: To digitize analog data continuously.

Speed: Up to 13,000 samples per second.

Output tape: Unlabelled 9-track. Data is in 32-bit floating point form.
1944 words per record (can be changed).
Can have multiple files (data sets).

Procedure: Same as ADC4.

DIAG1 Program

Purpose: To check A/D converter and I/O interface of processor.

Procedure: Load program with BBL.
Entry address is 100 octal. Push run.
Halt 77 - Ready. Push run to start.

Connect a d-c power supply ($0 \rightarrow \pm 10_V$) to the analog input and turn on the clock signal to the A/D converter. By slowly varying the input voltage the user can watch the B-register count up and down. The binary reading may be compared to the input voltage reading.

If bit SW 15 is set at any time, the program will halt back on Halt 77.

DIAG2 Program

Purpose: A magnetic tape reading program. Allows the operator to go forward or backwards on the tape in steps of records. Data on any record may be observed and tape marks are clearly indicated.

Procedure: Mount tape. Load program using BBL. Program entry is 100 octal. The first halt, Halt 76, is the starting point in the program. The "A" and "B" registers hold the number of the record of data presently directly behind the magnetic read read. Two operator options are possible at this point. Setting bit switches 14 and 15 causes the tape to backspace one record. Otherwise the next record is read in and Halt 0 is executed. The "A" register will contain the record length (up to 7400_8) and the "B" register will hold the record number. If the record read in is a tape mark, Halt 25 will be executed and 177777_8 will appear in the "A" register and "B" will hold the record number. Push run to read the next record.

Pushing run after Halt 0 allows the operator several options. One may look at the nth word on the tape record by entering n-1 into the switch register. That is, to look at the first word of the tape record, set the switch register to zero. To look at the second word, set the switch register to 1, etc. By setting switch bit "14" Halt 0 is executed with the registers holding the same information as before. Setting bit "15" returns the program to Halt 76 so the next record may be read, or the tape may be backspaced. The memory block area starts at 4000_8.

DIAG3 Program

Purpose: DIAG3 consists of two independent programs. The first is intended to aid in setting the offset voltage of the multiplexer. The second determines the peak input voltage to the A/D converter. The programs are located in memory such that they may be loaded and executed without destroying either the Magnetic Tape Operating System or the magnetic tape loading programs of the ADC series.

Procedure: Load the program tape using the BBL.

Entry 7000_8: Program acts as an integrator on the data from the A/D converter. Intended use is to set the offset voltage of the multiplexer.

Entry 7100: Program reads data from the A/D converter, removes sign and compares magnitude with largest magnitude received previously. If latest input is larger, the value is displayed in the "A: register. Intended use is to allow operator to adjust input voltages to the A/D converter such that it is not saturated on the peaks of the input waveforms.

The first program with starting address of 7000_8 reads data from the A/D converter and sums all the inputs together. That is, the program simulates an integrator. The integral is displayed in the "A" register at all times. The "A" register may be zeroed at any time by setting bit SW "15" of the switch register. To use the program, all inputs to the multiplexer should be removed, the multiplexer output connected to the A/D signal input, and a clock signal connected to the A/D trigger input. By watching the "A" register, the operator can determine if the average offset voltage is positive or negative. He can then turn the potentiometer to adjust the offset voltage the proper direction such that the integral tends to stay close to zero. The potentiometer is under the chassis of the multiplexer. However, it is located such that it may be adjusted while the multiplexer is in the relay rack. Experience has shown that it is usually best to have a slow clock rate when running this program.

The second program has an entry address of 7100_8. It reads data from the A/D converter, strips off the sign bit and compares the magnitude of the last data point with the largest data point received previously. If the last input is larger, it is displayed in the "A" register. Thus, the program tells the operator the peak input voltage to the A/D converter. Setting bit "15" of the switch register will reinitialize the program at any time.

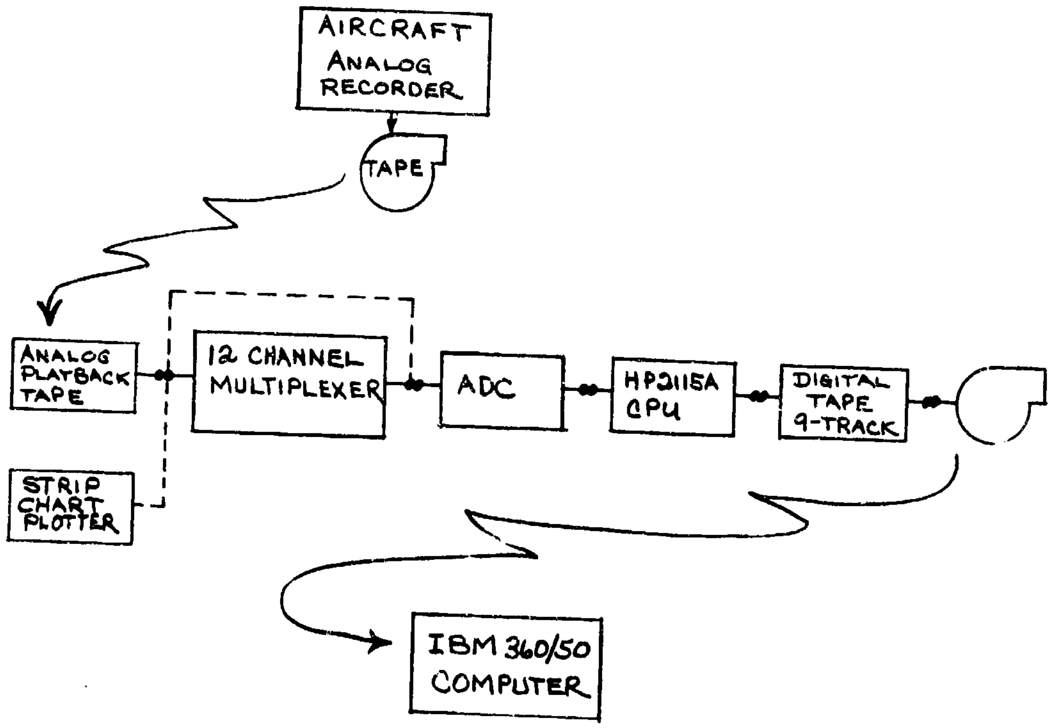


Figure 9. The Data Handling and Conversion System

Multiplexer. A multiplexer was designed and constructed which allows as many as 12 channels to be digitized simultaneously.

The analog portion of the multiplexer is depicted in Figure 10. The analog signals, which feed into terminals A1 through A12, originate from the playback Sangamo analog tape machine. These signals have levels that are normally in the 0 to 10 volt range. The preamplifiers in the multiplexer, PA1 to PA12, are designed to keep the signal levels at a maximum of ±10 volts.

When a sample command is received on terminal SC, the sample-hold integrators, SH1 through SH12, all go into HOLD at the same time. Then, in the interim period between this sample command and the next one, the data samples are fed, one at a time, to the analog-to-digital convertor (761A). This is accomplished by opening the electronic switches, SW1 through SW12, sequentially in turn. The commutating control signals for this purpose are applied to terminals S1 through S12 in Figure 10.

The maximum sampling rate of the system, with 12 channels operating, is limited first by the digital tape machine. The maximum sampling rate, per channel, is 1940 samples per second. This figure is arrived at by dividing the overall maximum speed of 25,250 samples per second by 13 (the number of intervals in the read-out process). Naturally if fewer channels were in operation, the maximum speed, per channel, would be faster.

The necessary timing signals to accomplish the desired sequencing of the HOLD and READ-OUT operations are shown in Figure 11. In Figure 12 is pictured the digital control system for producing the timing signals.

With reference to Figure 12, the process is started by enabling the GO line. This can be done manually with a switch, or it may be desirable at times to synchronize this with the analog playback tape machine. The output of the AND gate, AND1, will start the clock whenever the 2115A processor delivers a SET-CONTROL signal (approximately 2 μs max from GO). The one-shot, OS1, provides shaping of the clock pulses as well as providing a 10 μs delay for the ADC convert signal.

The first change of the ring-counter sets the HOLD flip-flop which, in turn, causes the sample-hold integrators to HOLD. Then, as subsequent clock pulses occur, the ring-counter steps through 13 intervals. The outputs of 12 of the ring-counter flip-flops are used to gate the electronic switches SW1 - SW12. The 13th interval allows the sample-hold integrators to go back to the track or sample states and to stay in that state long enough to assume stable tracking operation. The entire cycle is then repeated when the ring-counter starts its cycle again.

TABLE I

Identification of Analog and Digital Modules

PA	Type 3112/12C, Burr-Brown
BA	Type 3130/15 , Burr-Brown
SH	Type 4035/15 , Burr-Brown
SW	Type 9859/15 , Burr-Brown
Clock	Type R401 , Digital Equipment Corporation
OS	Type R302 , Digital Equipment Corporation
Inv	Type R107 , Digital Equipment Corporation
FF	Type R202 , Digital Equipment Corporation
NC1	Type W600 , Digital Equipment Corporation
NC2	Type W601 , Digital Equipment Corporation
AND1	Type R111 , Digital Equipment Corporation

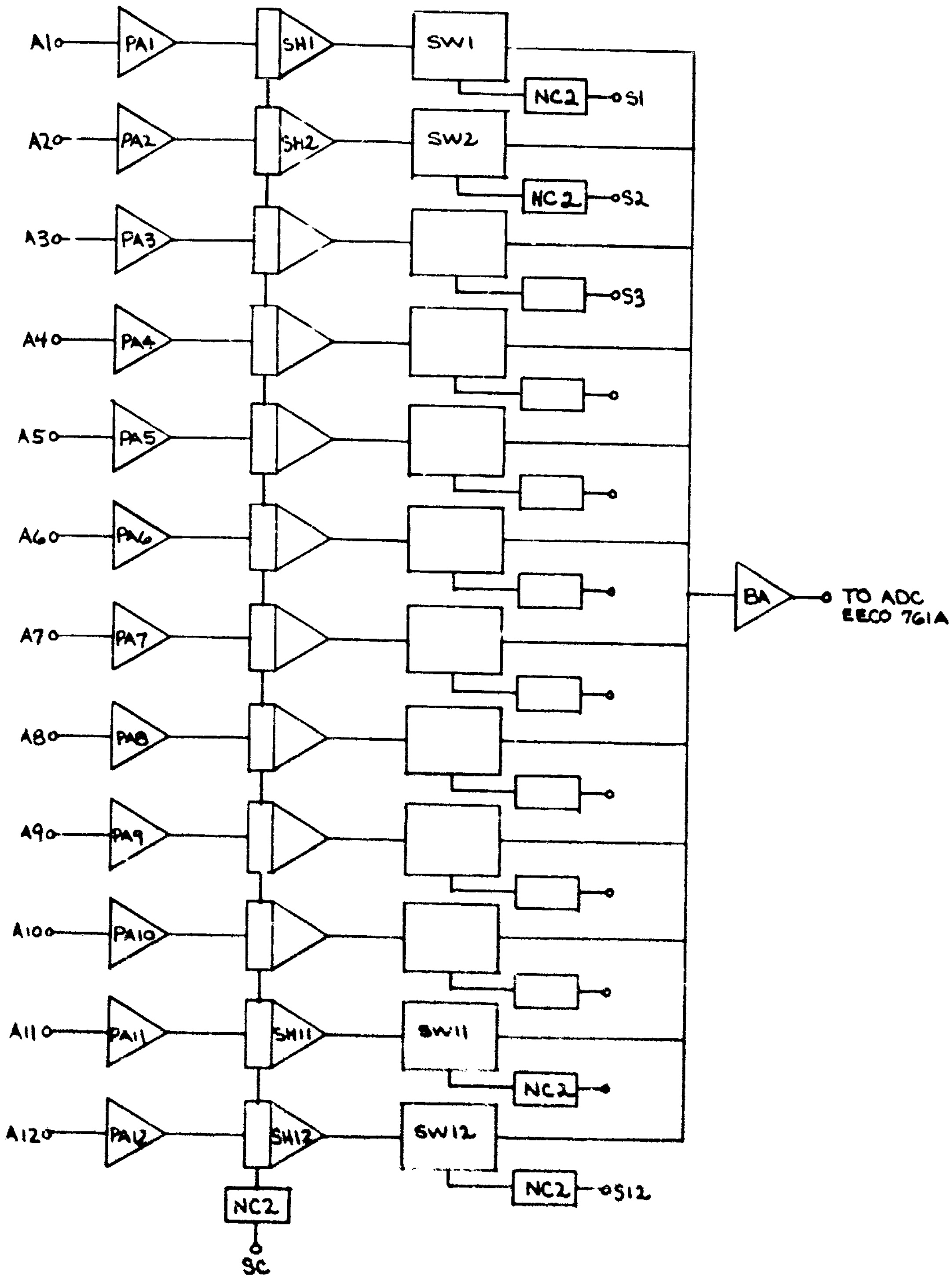


Figure 10. Analog Portion of Multiplexer

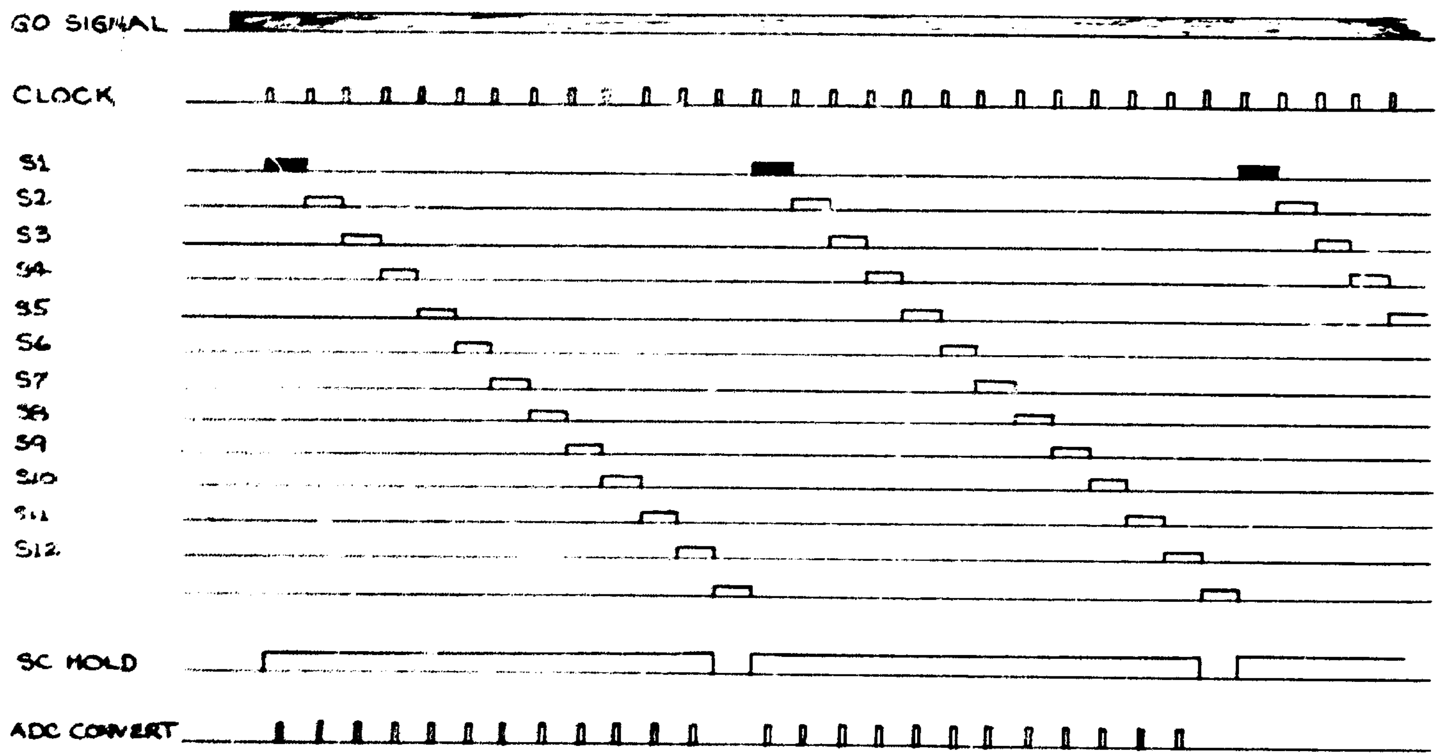


Figure 11 Digital Timing Signal Sequence

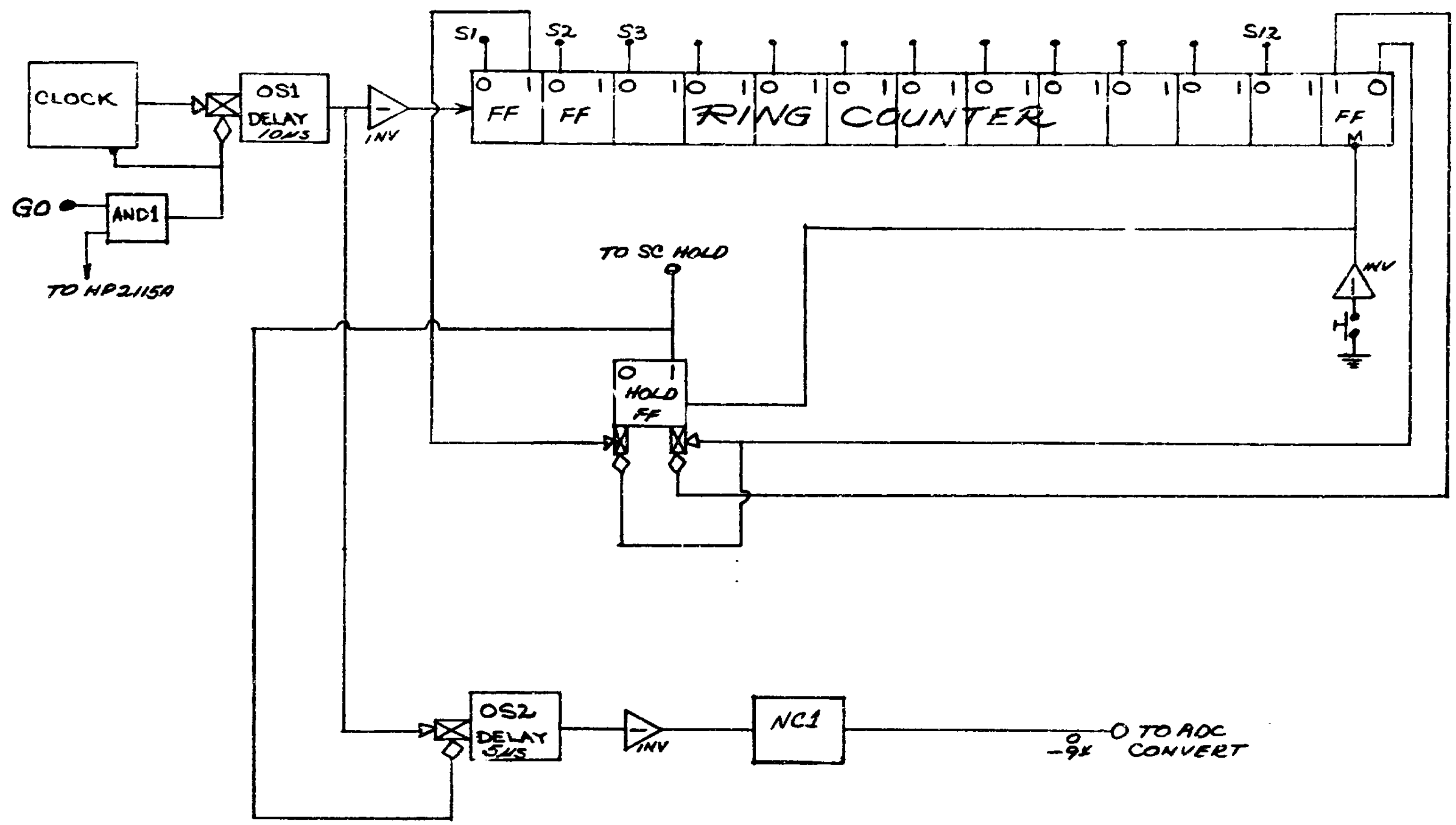


Figure 12. Digital Control System for the Multiplexer

Sferic Activity Meter. During the year, work has been done toward the development of a more universal sferic activity meter. This device is one embodying principles similar to that ι ed in producing the Sferic Rate Histories presented as Figure 2, page 9, of the Quarterly Report dated March 31, 1970.

The diagram of Figure 13 represents the present form of the sferic instrument and the general nature of its operation is as follows The input signal at terminal, T1, is the sferic signal from either a playback of an analog record or it can be originating in real-time from a detector output. In any event, it must be composed of positive signal bursts. Waveform, S1, of Figure 14 is representative of this signal.

The circuit is designed to accommodate an input signal, S1, with a minimum level of about 0.1 volt peak. The gain control P1, allows adjustment for larger signals.

The inverting amplifier, A1, has gain of 100. This builds up the maximum value of the signal to approximately 10 volts (negative peak). Control P2 sets the maximum negative limiting level of the amplifier to prevent overloading.

The Schmitt Trigger works as a discriminator against undesirable noise levels. The logic output levels of the trigger are 0 and -3 volts. The threshold levels at which the circuit switches are nominally -2.2 and -0.8 volts; however, these can be adjusted by pots P4 and P5 for changing the discriminating characteristics. The typical output of the Schmitt Trigger appears in Figure 14 as waveform S3.

The next stage, the one-shot multivibrator, OS, is for standardizing the widths of the pulses which coincide with sferic bursts. The adjustment of the pul: width is quite critical and the necessary width

is related to the nature of the sferic bursts. Waveform S4 of Figure 14 is representative of the output of the OS.

The special integrator, I1, serves as a short-time analog memory. In terms of the LaPlace Transform operator, S, this stage has a transfer function of

$$\frac{C_o}{C_1} = \frac{R_9}{R_8}\left[\frac{1}{1 + R_8CS}\right]$$

which shows the state to be a first-order log function. The time constant of the special integrator has three selections controlled by switch SW1. They are 70, 45 and 15 seconds, respectively. S5 waveform in Figure 14 serves to show the action of this stage.

The amplifier A2 serves merely to interface the resulting signal from the integrator to a recording meter M1. The present recorder, a RUSTRAK, requires 1 ma for full-scale deflection. Amplifier A2 has normal gain of 2.

In order that the sferic activity meter be suitably responsive to varied storm conditions, the threshold levels of the Schmitt Trigger, the plus width of the one-shot and the time-constant (and gain) of the 1st-order lag integrator must be coordinated suitably. Studies and experiments along this vein are continuing.

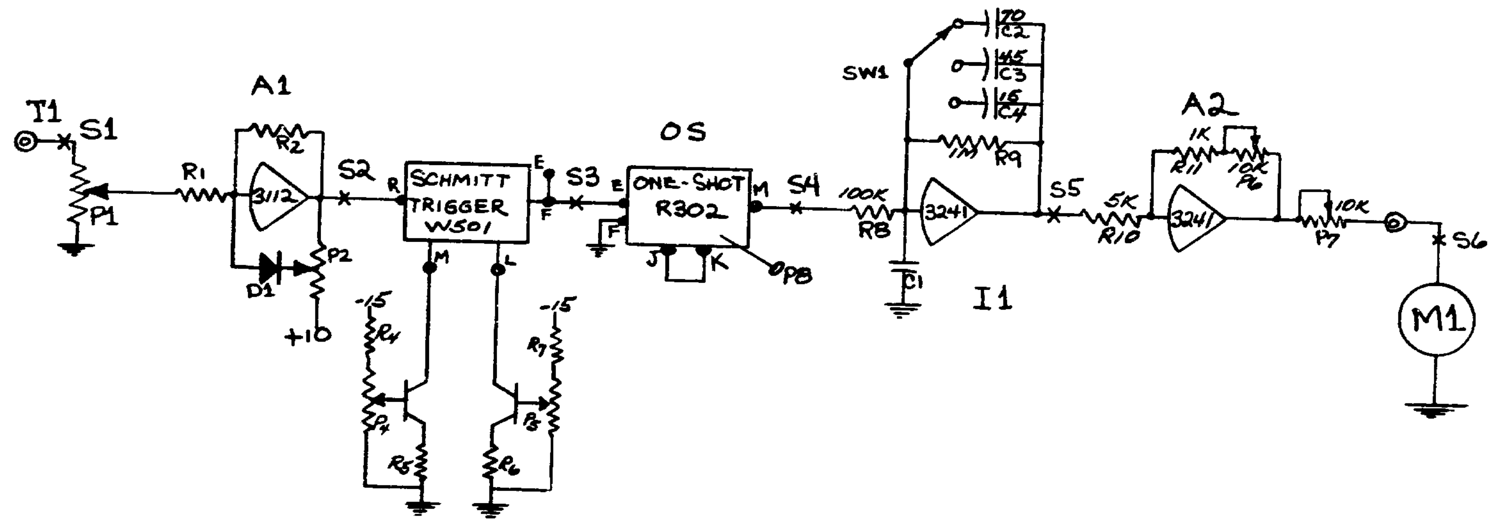


Figure 13. Diagram of the Sferic Activity Meter

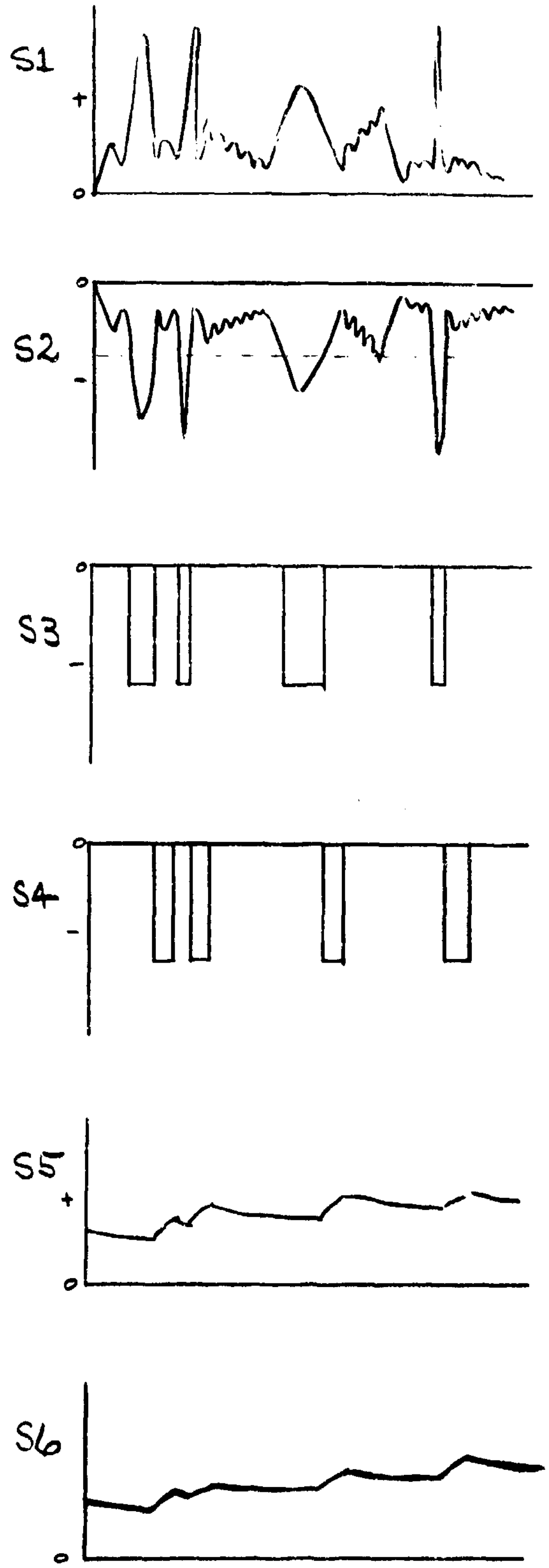


Figure 14. Signal Waveforms

APPENDIX A

Name: Kumarasamy Shanmugam Date of Degree: May 25, 1970

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: LEARNING TO RECOGNIZE PATTERNS WITH AN IMPERFECT TEACHER

Pages in Study: 104 Candidate for Degree of Doctor of Philosophy

Major Field: Electrical Engineering

Scope and Method of Study: Most of the earlier research efforts in pattern recognition have been directed towards developing procedures for learning to recognize patterns with a perfect teacher. In recent years considerable attention has been given to the problem of learning without a teacher. In between these two vastly different classes of problems is the problem of learning to recognize patterns with an imperfect teacher. This dissertation develops procedures for learning to recognize patterns with an imperfect teacher. The result is a nonparametric learning procedure. Theorems concerning the derivation of the learning procedure and analysis of performance are presented. The concept of feedback in the proposed learning scheme is investigated and a feedback learning scheme is proposed. The proposed feedback learning scheme is simulated on the computer and the results on the performance of the learning schemes are given. A comparison of the performances of the learning scheme with feedback and learning scheme without feedback is presented.

Findings and Conclusions: The proposed learning scheme is asymptotically optimal in the sense that it has an average risk equal to Bayes' (minimum) risk. If the density functions do not overlap then the average asymptotic performance of the learning scheme is better than the nearest neighbor rule and the imperfect teacher. The above results are true with a finite sample size also. For overlapping densities if the Bayes' risk is less than $(1-\beta)$, β being the probability that the teacher classifies a sample correctly, then the proposed learning scheme is still better than the nearest neighbor rule and the imperfect teacher. Also the proposed learning scheme does not require a knowledge of the exact value of β.

The thresholded feedback scheme proposed provides a deterministic method for combining the knowledge acquired by the learning scheme with that provided by the imperfect teacher. Threshold also provides control over the amount of feedback and facilitates a gradual phasing out of the teacher. If the density functions do not overlap then feedback results in an improvement in the average performance of the learning scheme. With overlapping densities such an improvement is possible only for low values of β. Further research needs to be done on using feedback with overlapping densities, on using a probabilistic feedback.

Name: Richard Leon Johnson Date of Degree: May 16, 1971

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: A STUDY OF THE SECOND-ORDER STATISTICAL PROPERTIES OF THUNDERSTORM NOISE

Pages in Study: 143 Candidate for Degree of Doctor of Philosophy

Major Field: Electrical Engineering

Scope and Method of Study: This investigation was undertaken to develop a second-order statistical description of the thunderstorm signature as a source of noise interference. A characterization was obtained under three constraining conditions: (1) the data were gathered at a distance of thirty kilometers from the storm; (2) measurements of the storm signature were taken over the VLF portion of the radiated spectrum; and (3) the study was specialized to the segments of data which exhibited intense sferic activity. The data were, first, analyzed to determine whether or not a stationary assumption would be valid. It is shown that the sferic triggering mechanism can be modeled by a Poisson impulse process. Based on the assumption of wide sense stationarity, estimates of the time averaged autocorrelation and power spectral density functions are computed from three data segments of 0.75 second duration. These estimates are then, averaged to form an improved estimate.

Findings and Conclusions: The assumption of stationarity in the wide sense appears valid for data segments evidencing extremely intense sferic activity. Using a wide sense stationary model, estimates of the time averaged autocorrelation and power spectral density functions, computes from three member functions of the ensemble, were found to be strikingly similar after being normalized to the average measured power. Because of the close resemblance, it is concluded that the mean of the time averaged autocorrelation and power spectral density estimates is a reasonable description of the process in an ensemble sense. Specifically, it appears likely that this is a representative description of data segments evidencing extremely intense sferic activity. It is believed that this description may be useful in the design of filters for the purpose of minimizing thunderstorm noise interference in a mean square sense.

DISCRIMINATING BETWEEN CLOUD-TO-GROUND AND CLOUD-TO-CLOUD LIGHTNING DISCHARGES: A PATTERN RECOGNITION APPROACH

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ABSTRACT

A procedure for classifying lightning discharges into cloud-to-ground or cloud-to-cloud type is developed. This classification procedure is based on a set of measurements indicative of the frequency content of both horizontally and vertically polarized sferic signals from lightning discharges. The data corresponding to 84 visually identified discharges from one storm were used to develop the classification procedure. Additional data corresponding to 50 identified discharges from another storm were used to test the resulting classification scheme. Up to 82 percent agreement was found, on the test samples, between visual identification of the discharge and the type given by the classification scheme.

We found that significant difference exists in the frequency content of the horizontally polarized sferic signal from cloud-to-ground and cloud-to-cloud discharges. Also, the polarization ratio of the signal in the 50 kHz range was found to be considerably different for the two types of discharges.

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INTRODUCTION.

Considerable progress has been made during the past 30 years in the study of sferics from lightning discharges. Most of the earlier research attempts in this area have been directed towards understanding the nature of cloud-to-ground discharges. In recent years, efforts have been made towards the investigation of the nature of cloud-to-cloud discharges (Ogawa, T., and M. Brook, 1964) and towards finding out and explaining the differences in the sferic signals from different types of discharges (N. Kitagaw and M. Brook, 1960). This paper examines the differences in the frequency content of the sferic signal from cloud-to-cloud and cloud-to-ground discharges.

The frequency content of the sferic signal from lightning discharges have been studies by many investigators (Arnold and Pierce, 1964; Dennis and Pierce, 1964; Taylor, 1963). Most of the studies in this area are based on measurement of vertically polarized sferic signals recorded on the surface of the earth. By means of airborne instrumentation, both horizontally and vertically polarized sferic signals from lightning discharges were recorded and analyzed. Significant differences in the frequency content of the sferic signal from cloud-to-ground and cloud-

to-cloud discharges are pointed out and a procedure is given for discriminating between these two types of discharges in the absence of visual identification.

INSTRUMENTATION AND DATA GATHERING.

From the boundary conditions imposed on Maxwell's equations it follows that the horizontal polarization of the sferic signal cannot be measured effectively on the ground at low frequencies. Hence, airborne instrumentation was used in this investigation. Also, the airborne instrumentation made it possible to stay close to a moving storm and collect data for a reasonably long time. The antenna complement of the instrumentation consists of a vertical whip antenna mounted on top of the fuselage of the research aircraft (D-18S Beechcraft) and a horizontal tow-type antenna attached to a cable which unreels from the tail of the aircraft. The signal flow path, which is identical for both horizontal and vertical antennas, is shown in Figure 1.

The signal gathered at the antenna is routed through a cathode follower, pre-amp, cathode follower assembly to a set of comb filters. The filters used have center frequencies of 10kHz, 50kHz, 150kHz and 250kHz and a bandwidth of 1 kHz. The output of each comb filter is then envelope detected with a detection time constant of 1 millisecond. The detected signal is then recorded in FM mode on one of the 12 data channels of a magnetic tape recorder. In addition to the sferic data, one of the edge tracks of the tape contains an audio recording of the comments of an observer in the aircraft. These comments, recorded in real time along with the sferic data, contain information about the type of discharges that were visually identified by the observer in the aircraft. When the sferic data is played back, the voice recording

serves to identify a burst of data as coming fron a cloud-to-ground or cloud-to-cloud discharge.

The data used in this investigation were taken during two thunderstorms in Oklahoma during June, 1969. Both the storms were of frontal type and had a large number of well defined lightning discharges. The aircraft was flying elliptical paths on one side of the storms at a distance of approximately 30 kilometers and an altitude of 5 kilometers. The data corresponding to 50 discharges from the storm on June 11, 1969 and 84 discharges from the storm on June 22, 1969 were processed for a set of measurements as described below.

DATA REDUCTION.

The first step in data reduction was converting the analog data into digital form suitable for processing on the digital computer. Sections of recorded data corresponding to visually identified, well defined discharges were selected and the analog data was converted into digital form. The average duration of the signal from the discharges was about 3/4 second and the digital data for the duration of the individual discharges were processed for a set of measurements which served as inputs to the pattern recognition scheme.

The measurements derived from the data consists of the relative amounts of energy in the various comb filter frequencies. Even though one would normally require exact values for these measurements for a quantitative analysis, a relative measure of these values will be adequate for pattern recognition purposes.

The energy received from a discharge at the input of a particular comb filter channel is the product of the average power, N, at the input

and the duration T of the discharge. Since T is the same for all frequencies for a given discharge, the average value of power at the input to the filter is sufficient for comparing the relative amounts of energy in various comb filter bands. For small amplitudes, the envelope of the comb filter output has been shown (Horner, F., 1964) to have a Raleigh distribution with a mean equal to $\sqrt{N\pi/2}$. Hence the average value of the comb filter output is a relative measure of N, the average power at the input and hence a measure of energy.

Since the received energy is a function of the distance between the aircraft and the discharge and since this varies from discharge to discharge, the average value of the signal in various comb filter channels were normalized as follows: The average value of the signal in each of the four horizontal channels was normalized with respect to the sum of averages in all horizontal channels. This gives a relative measure of the fraction of horizontally polarized energy that appears in a given comb filter band of frequencies. Similarly, the averages in the vertical channels were normalized with respect to the sum of averages in all the vertical channels. The sum of averages in horizontal and vertical channels were normalized with respect to the total sum to obtain fractions of total energy that are horizontally and vertically polarized. In addition to these 10 measurements the average values of signal in 50 kHz horizontal and vertical channels, normalized with respect to their sum were taken to represent the polarization ratio in 50 kHz range. This set of twelve measurements are listed below.

x_1 - Normalized average value of signal in 10 kHz Horizontal

x_2 - Normalized average value of signal in 50 kHz Horizontal

x_3 - Normalized average value of signal in 150 kHz Horizontal

x_4 - Normalized average value of signal in 250 kHz Horizontal

x_5 - Normalized average value of signal in 10 kHz Vertical

x_6 - Normalized average value of signal in 50 kHz Vertical

x_7 - Normalized average value of signal in 150 kHz Vertical

x_8 - Normalized average value of signal in 250 kHz Vertical

x_9 - Normalized sum of average value of signal in horizontal channels

x_{10} - Normalized sum of average value of signal in vertical channels

x_{11} - Normalized horizontal signal in 50 kHz channel

x_{12} - Normalized vertical signal in 50 kHz channel

Since x_4, x_8, x_{10} and x_{12} can be calculated if the other measurements are known, these were eliminated as inputs to the pattern recognition scheme. The remaining 8 measurements were used to form a "pattern vector" X from the data corresponding to each identified discharge, where

$$X = [x_1, x_2, x_3, x_5, x_6, x_7, x_9, x_{11}]^T$$

For sample patterns used to train the pattern classifier, information about the type of discharge to which a particular pattern X_i corresponds is needed as an input to the classifier. This identification information, denoted by θ^i, comes from visual sightings of the discharge by the observer in the aircraft. If θ_1 and θ_2 denote cloud-to-ground and cloud-to-cloud discharges respectively, then θ^i takes the form $\hat{\theta}_1$ or $\hat{\theta}_2$ depending on if X_i corresponds to a discharge identified as cloud-to-ground or cloud-to-cloud type. Combining this information with X_i, the data presented the pattern recognition scheme consists of a set of measurement pairs $(X_1,\theta^1), \ldots, (X_n,\theta^n)$.

PATTERN RECOGNITION.

The pattern recognition problem in this investigation consists of developing procedures for identifying cloud-to-ground and cloud-to-cloud discharges based upon the sferic signals. The classification procedure is developed from a given set of measurement pairs $(X_1,\theta^1), \ldots, (X_n,\theta^n)$. After the development of a classification procedure, only the measurement X is available and an estimate is desired of the type of discharge from which X was derived. Three methods described below were used for developing such procedures based on a set of n measurement pairs.

1. Polynomial Discriminant Function Method: For probabilistic pattern sets, a Bayes' procedure for classifying patterns into $\hat{\theta}_1$ or $\hat{\theta}_2$ with minimum probability of misclassification uses a discriminant function of the form,

$$D(X) = P(\hat{\theta}_1)\, f_{X|\hat{\theta}_1} - P(\hat{\theta}_2)\, f_{X|\hat{\theta}_2}, \tag{3}$$

where $P(\hat{\theta}_i)$ is the probability that a measurement X has a visual identification $\hat{\theta}_i$, and $f_{X|\hat{\theta}_i}$ is the conditional probability density function of X given that X is visually identified as $\hat{\theta}_i$. A given pattern X is assigned to $\hat{\theta}_1$ if $D(X) > 0$ and to $\hat{\theta}_2$ if $D(X) < 0$. Since no knowledge about $P(\hat{\theta}_i)$ and $f_{X|\hat{\theta}_i}$ is assumed, these quantities have to be estimated from the given sample patterns.

The quantity $P(\hat{\theta}_i)$ was estimated by

$$\hat{P}(\theta_i) = \frac{n_i}{n},$$

where n_i is the number of sample patterns with the identification $\hat{\theta}_i$ and n is the total number of samples. The unknown densities $f_{X|\hat{\theta}_i}$ were

estimated in the form of a second order polynomial in the components of X, as proposed by Specht (1967). Using the estimated probabilities and density functions in Equation (3), the estimated discriminant function

$$\hat{D}(X) = \hat{P}(\hat{\theta}_1)\, D_1(X) - \hat{P}(\hat{\theta}_2)\, D_2(X) \qquad (4)$$

was used to classify X into $\hat{\theta}_1$ or $\hat{\theta}_2$ depending on if $\hat{D}(X) > 0$ or $\hat{D}(X) < 0$. In Equation (4), for i = 1 or 2 $D_i(X)$ is the polynomial estimator of $f_{X|\hat{\theta}_i}$ whose coefficients were computed from the sample patterns identified as $\hat{\theta}_i$. Expressions for computing and updating these coefficients were given by Sprecht (1967).

2. Threshold Logic Unit: In the threshold logic unit method, a linear discriminant function of the form

$$D(X) = w_1 x_1 + w_2 x_2 + \dots + w_d x_d + w_{d+1} \qquad (5)$$

was used to classify X into $\hat{\theta}_1$ or $\hat{\theta}_2$ depending on whether $D(X) > 0$ or $D(X) < 0$. In Equation (5), d is the number of measurements used, $x_1, \dots, x_d$ are the components of the pattern vector X and $w_1, w_2, \dots, w_{d+1}$ are a set of weights determined through an error correcting procedure (Nillson, 1965). The correction factor in this procedure was made to decrease as $1/(m+1)$ where m denotes the number of training cycles completed. The weight vector that resulted at the end of 1,000 training cycles was used in Equation (5) for classifying the test patterns.

3. Linear Least Square Method: A linear discriminant function of the form given in Equation (5) was used in this method also. However, the weight vectors were chosen such that the sum $\sum_{i=1}^{n} (Y_i - w_{d+1} - W^T X_i)^2$ is minimized, where

$Y_i = +1$ if X_i has an identification $\hat{\theta}_1$

$Y_i = -1$ if X_i has an identification $\hat{\theta}_2$

and

$$W = (w_1, w_2, \ldots, w_d)^T.$$

RESULTS.

Data corresponding to 84 discharges from one storm, consisting of 42 cloud-to-ground discharges and 42 cloud-to-cloud discharges were used to "train" the pattern classifier. Fifty additional samples from a different storm were used to test the performance of the trained classifier. The index of performance was the percentage agreement between the identification provided by the classifier and the visual identification of the test samples.

The classifier was first trained with all the eight measurements as inputs to the classifier. At the end of training, it was observed that the weights attached to measurements x_1, x_2 and x_{11} were large in magnitude compared to the other measurements. This suggested that x_1, x_2 and x_{11} are more significant than the remaining measurements. So the classifier was trained again with x_1 and x_2 and also with x_1, x_2 and x_{11}. The summary of performance of the classifier for the three different methods of training with three different input measurement sets is given in Table I. The entries in the table represent the percentage agreement between the classification provided by the pattern recognition scheme and visual identification on the 50 test samples.

It can be seen from Table I, that the best classification scheme is the one using x_1, x_2 and x_{11} as input measurements. A scatter diagram of the training patterns with respect to these measurements is shown in Figures 2 and 3. The following observations can be made from these Figures.

(1) Cloud-to-cloud discharges tended to have more horizontally polarized energy in 50 kHz range while cloud-to-ground discharges tended to have more horizontally polarized energy in 10 kHz range.

(2) Cloud-to-ground discharges tended to have more vertically polarized energy in 50 kHz range while cloud-to-cloud discharges tended to have more horizontally polarized energy.

The differences in frequency content of the two types of discharges can be explained in terms of the physical lengths of the discharge paths, the magnitude of currents and the rates at which they change. In a cloud-to-ground discharge, two main sources of radiation are the step leader and the return strokes. Return strokes, which are strong and contain large slowly changing currents, radiate maximum energy in 5-10 kHz range (Uman, 1969; Dennis and Pierce, 1964). Return strokes may also have continuing current with energy in the ELF range. The cloud-to-cloud discharges do not have return strokes of the same form as those in a cloud-to- ground discharge. They may radiate low frequency energy comparable with but usually smaller than that from return strokes (Horner, 1964), hence cloud-to-cloud discharges have comparatively smaller energy in the lower frequencies.

The difference in polarization can be attributed to the physical orientation of the discharge, the cloud-to-ground discharges having more of a vertical orientation. The average value of the percentage of horizontally polarized energy in 50 kHz range for the cloud-to-ground discharge was found to be 39.85% and was 49.10% for cloud-to-cloud discharges. This 39.85% horizontal polarization for cloud-to-ground discharges suggests that the horizontal component of the in-cloud

channel on the average is comparable to the vertical component. Based on a study of electric field changes involving 539 return strokes involving 84 flashes, T. Ogawa and M. Brook (1969) concluded that the horizontal component of the in-cloud channel is significant and on the average exceeds the vertical component. Our results support the conclusions of T. Ogawa and M. Brook to the extent that there is signigicant horizontal component in cloud-to-ground discharges. Since four channels that we used did not encompass the entire range of frequencies containing energy, further interpretation of our results is not possible.

The performance of the classification procedure evaluated by checking for agreement with visual identification does not give a measure of the true performance of the classifier. If β^* is the probability that the computer gives correct identification, and if β is the corresponding probability for visual identification, then the probability of agreement between the two is $\beta\beta^* + (1-\beta)(1-\beta^*)$. If β and $\beta^* > 1/2$, then the probability of agreement given in table one will be less that β^* that the probability classification scheme gives correct performance, i.e., the true performance index of the pattern recognition scheme will be higher than the probability of agreement given in table one. (Shanmugam and Breipohl, 1970).

CONCLUSIONS

It has been shown that measurements from sferic data can be used to identify cloud-to-cloud and cloud-to-ground discharges. There are significant differences in the frequency spectrum of the horizontally polarized sferic signal and the differences are significant in the horizontal vs vertical polarization ratio of the sferic signal in 50 kHz range. Combining these two measures we found that the identification provided

by the pattern recognition scheme agreed up to 82% with visual observations.

ACKNOWLEDGEMENT.

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Table 1. Summary of Performance

Input Measurements	Percentage Agreement with Visual Identification		
	Polynomial Discriminant Function Method	Threshold Logic Unit	Linear Least Sq. Method
All	70%	74%	80%
x_1, x_2	72%	78%	74%
x_1, x_2, x_{11}	76%	80%	82%

LEGEND FOR FIGURES

Figure 1. Block Diagram of Instrumentation.

Figure 2. Horizontally polarized Energy in 10 kHz Vs 50 kHz.

Figure 3. Horizontal Vs Vertical Polarization in 50 kHz band. All the points in this diagram lie along the line $x_{11} + x_{12} = 100$, but for the sake of clarity they are shown with an offset.

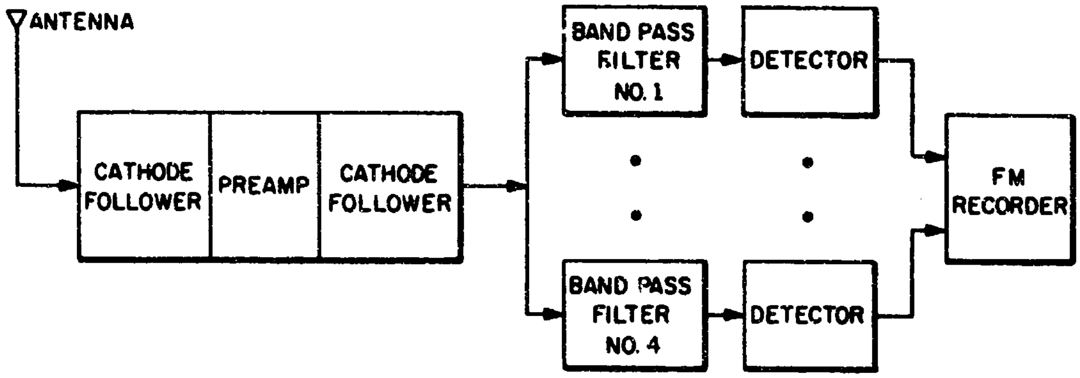
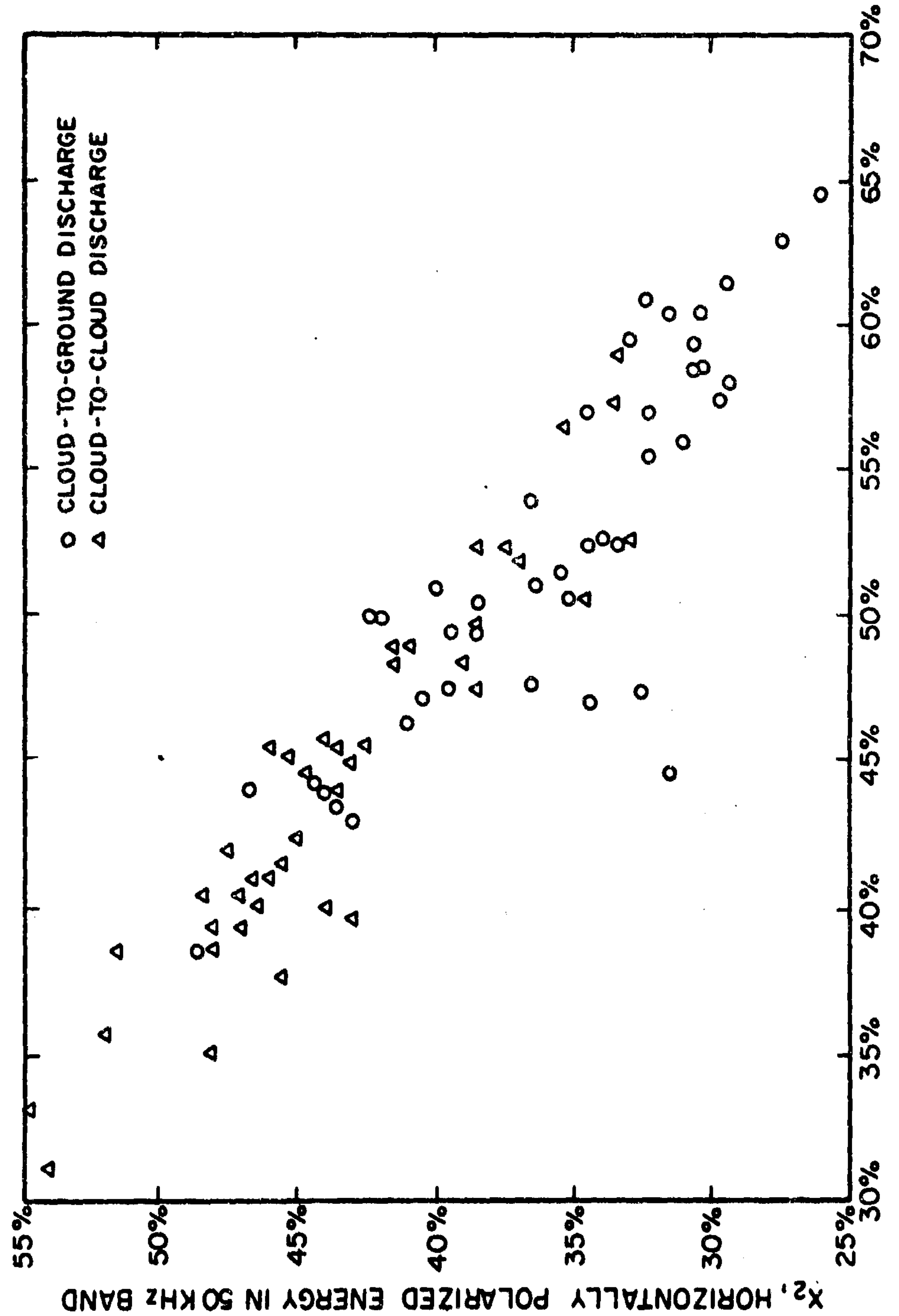
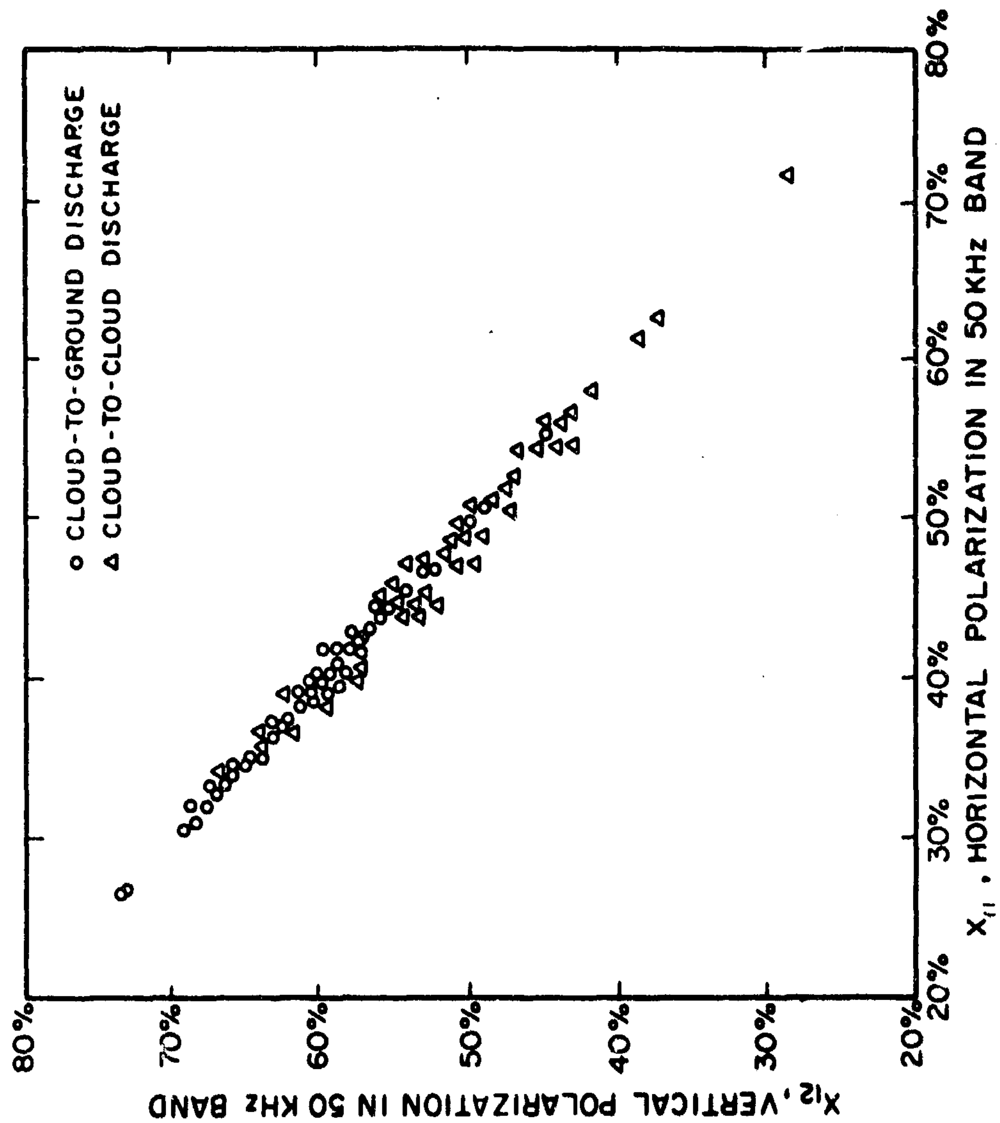

ANTENNA
CATHODE FOLLOWER
PREAMP
CATHODE FOLLOWER
BAND PASS FILTER NO. 1
DETECTOR
BAND PASS FILTER NO. 4
DETECTOR
FM RECORDER

Figure 1.



CLOUD-TO-GROUND DISCHARGE
CLOUD-TO-CLOUD DISCHARGE
X_1, HORIZONTALLY POLARIZED ENERGY IN 10 KHz BAND
X_2, HORIZONTALLY POLARIZED ENERGY IN 50 KHz BAND
30%
35%
40%
45%
50%
55%
60%
65%
70%
25%
30%
35%
40%
45%
50%
55%

Figure 2.



o CLOUD-TO-GROUND DISCHARGE
Δ CLOUD-TO-CLOUD DISCHARGE
X_{11} , HORIZONTAL POLARIZATION IN 50 KHz BAND
X_{12} ,VERTICAL POLARIZATION IN 50 KHz BAND
20%
30%
40%
50%
60%
70%
80%

Figure 3.

A STUDY OF THE SECOND-ORDER STATISTICAL PROPERTIES OF THUNDERSTORM NOISE

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Measurements were taken of the electromagnetic field radiated from two thunderstorms which were separated in time by three days. Analysis of two data segments from the first storm and one segment from the second storm revealed that the signature fit a wide sense stationary model; moreover, estimates of the autocorrelation and power spectral density functions indicate that the process satisfies a condition of local ergodicity. The study culminates in a second-order statistical description which appears to be valid in an ensemble sense.

As a part of the weather phenomena research work sponsored by the Department of Defense under Project Themis (A Center for Description of Environmental Conditions, Themis Project No. 129), atmospheric noise measurements were made in the presence of thunderstorm activity occurring in the vicinity of Rapid City, South Dakota in July 1969. The vertically polarized electromagnetic field radiated from the storm was sensed by a 1.525 meter vertical whip antenna mounted atop the fuselage of a D-18 twin engine Beechcraft airplane. The data were collected and recorded by magnetic tape on board the airplane while the aircraft flew in an elliptical path at an altitude of approximately 5 km. The flight path was centered approximately 30 km from the storm and was executed by

flying parallel to the storm for 10 min., making a 180^{0} turn, and flying in the opposite direction for 10 min. The objective was one of maintaining the path as near constant as possible with respect to the storm.

Three representative data segments of 0.75 sec. duration were selected for detailed analysis. These segments were characterized by a relatively high density of large amplitude K-change pulses, but were otherwise arbitrarily chosen (for a discussion of K-change pulses see Uman [1969]). Two of the data segments were taken from the data collected on July 14 and the third segment was taken from the recorded data of July 17.

The objective of the data analysis was to produce a credible estimate of the autocorrelation and power spectral density functions by serially reducing each data segment. In order to effect this analysis, the process was first investigated to determine the degree of stationarity. To test for stationarity in the wide sense, we hypothesized that the sferic triggering mechanism could be modeled by a Poisson impulse process. The condition of wide sense stationarity would be determined by whether or not the Poisson parameter were constant and the sferic pulses bore reasonable similarity. For illustration, let h(t) characterize a single K-change pulse and let λ denote the Poisson parameter. The process described is shot noise, and for a zero mean value, Papoulis [1965] shows that the autocorrelation function is represented by

$$\phi(t_1,t_2) = [\lambda(t_2)\, h(t_1 - t_2)] * h(t_2)$$

where * denotes convolution. If λ is constant, then Papoulis [1965] shows that the autocorrelation depends only on the parameter $\tau = |t_1 - t_2|$ and is given by

$$\phi(\tau) = \lambda \int_{-\infty}^{\infty} h(\tau + \beta)\, h(\beta)\, d\beta \quad .$$

Furthermore, when the triggering mechanism is characterized by a constant λ, Hogg and Craig [1965] show that the waiting time between pulses has a probability distribution function represented by

$$F_W(\omega) = \begin{cases} 0 & \omega < 0 \\ 1-e^{-\lambda\omega} & \omega \geq 0 \end{cases}$$

This implies that

$$\lambda\omega = -\ln[1 - F_W(\omega)] \quad \omega > 0$$

and if $-\ln[1 - F_W(\omega)]$ is plotted as a function of ω, the contancy of λ can be tested by whether or not the result is a straight line.

Measurements of the waiting times between pulses were taken from each of the data segments separately, and an empirical distribution function was computed. A plot of $-\ln[1 - F_W(\omega)]$ versus ω, then, revealed that a straight line approximation to the data points provided a reasonable fit. Hence, we concluded that a Poisson model with a constant parameter was a reasonable description of these segments of the storm signature. Further, we concluded that the data could be reduced using the methods of stationary analysis.

The autocorrelation and power spectral density functions were estimated from each of the three records. These estimates were strikingly similar after being normalized to the average measured power on each data segment. Because of the close resemblance in the estimates, we concluded that the process can be credibly represented by computing a sample mean based on the individual curves. The computed mean of the three autocorrelation functions is shown in Figure 1, while the mean of the power spectral densities is shown in Figure 2 Inspection of the power spectral density plot reveals a peak at 9 kHz which was expected

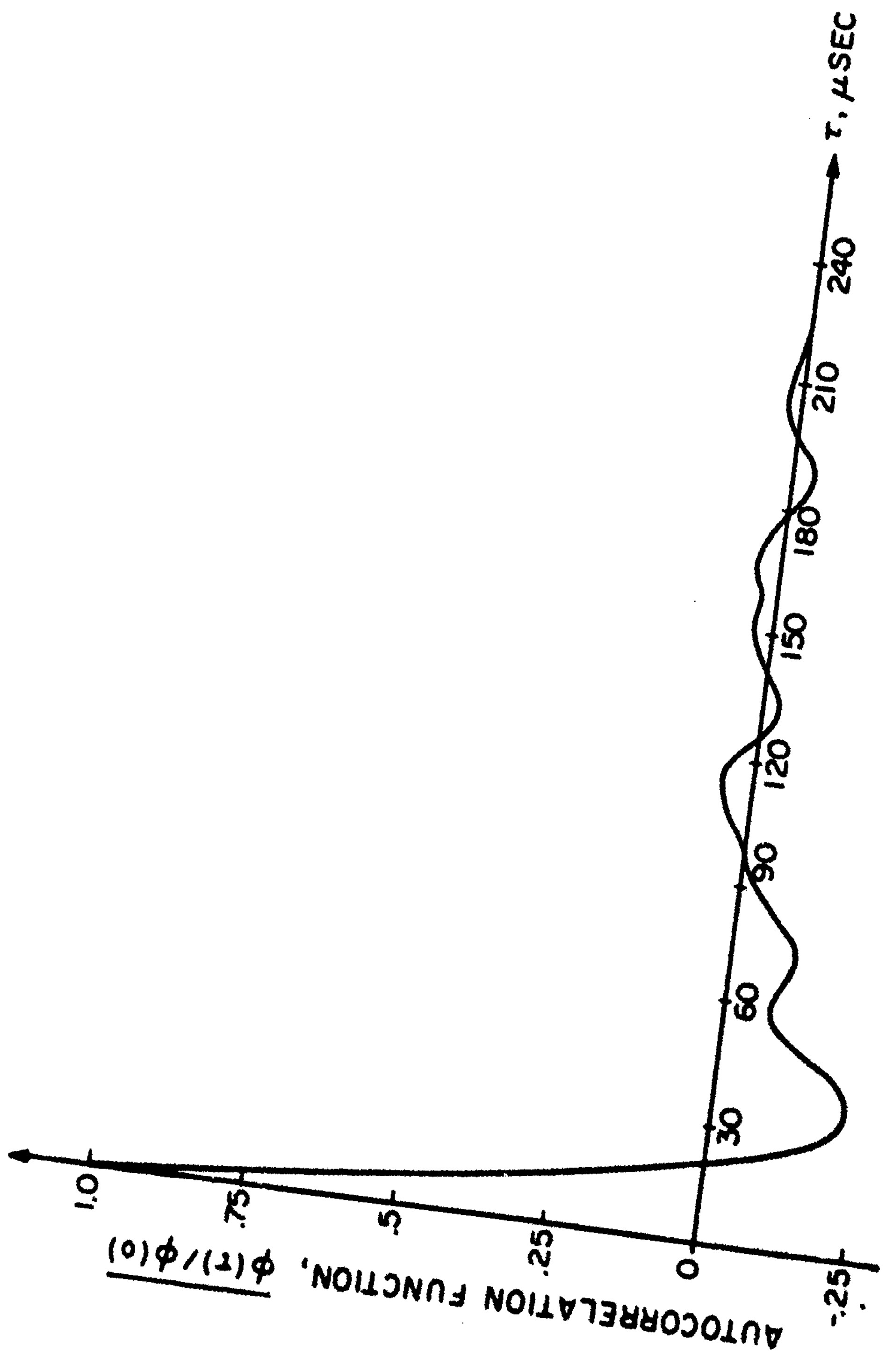

Figure 1. Averaged Autocorrelation Estimate.

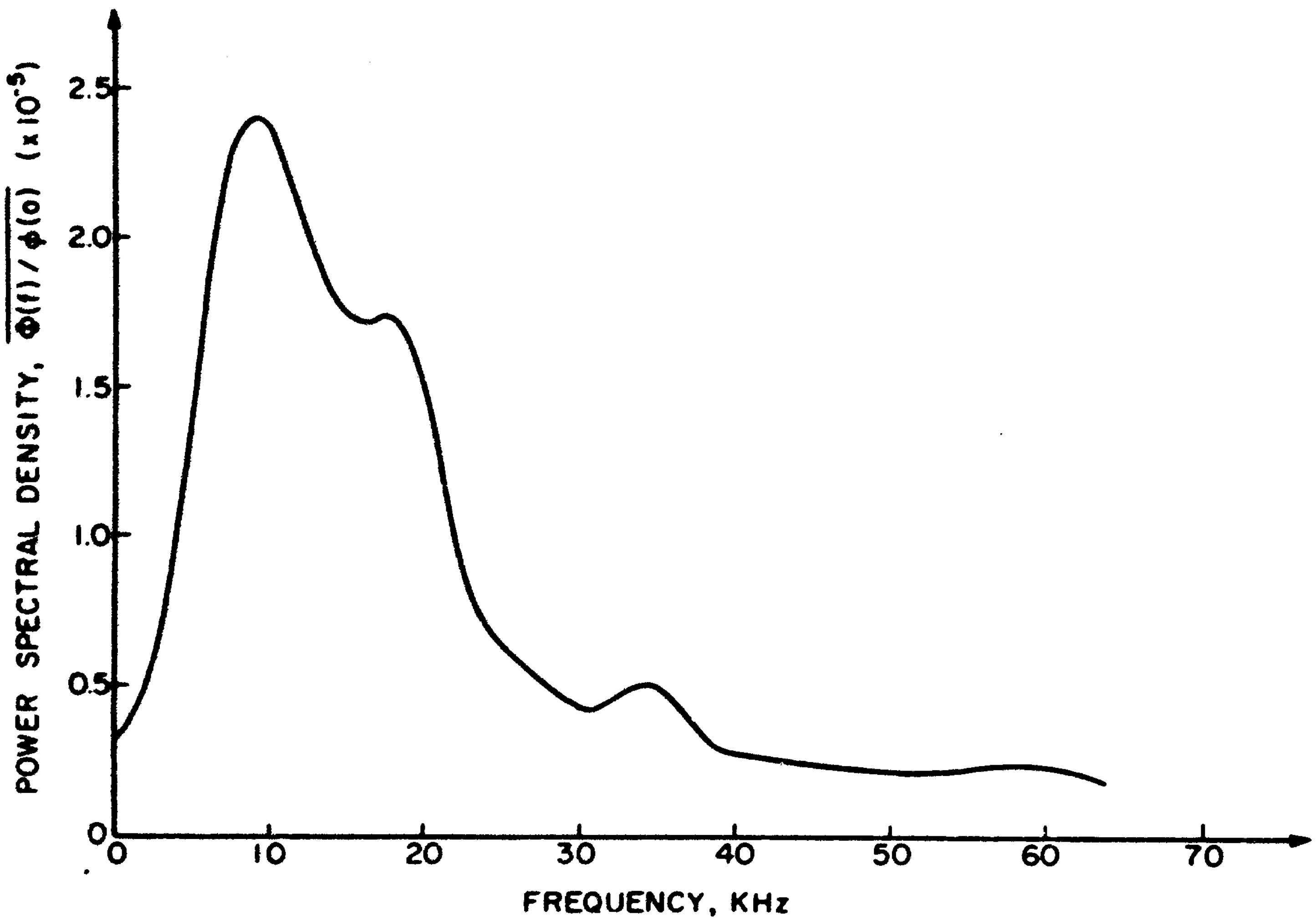

Figure 2. Averaged Power Spectral Density Estimate.

The hump at 18.75 kHz results from an interfering signal in the aircraft electrical system. The hump at 34.5 kHz was thought at first to be constructive interference from ground reflection or from the ionosphere; however, this component did not appear in the power spectral density of the first data segment. Because there were several sustained discharges of 30 msec duration or greater in the second and third data segments, but there were no discharges of this type in the first data segment, we speculated that the sustained discharges promote the radiation of this component although the cause for this phenomenon is unknown.

Summarizing, the assumption of stationarity in the wide sense appears justified for data segments evidencing relatively uniform intense sferic activity. Using the wide sense stationary model, estimates of the autocorrelation and power spectral density functions exhibit the ergodic property after being normalized to the average measured power. Because the data segments analyzed are believed to be representative, it appears reasonable to assume that the descriptions presented are valid in an ensemble sense for data segments of relatively uniform intense sferic activity.

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LEARNING WITH AN IMPERFECT TEACHER

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Summary

Most of the earlier research efforts in pattern recognition have been directed towards developing procedures for learning to recognize patterns with a perfect teacher. In recent years considerable attention has been given to the problem of learning without a teacher. In between these two vastly different class of problems is the problem of learning to recognize patterns with an imperfect teacher. This paper is concerned with developing and analyzing a procedure for learning to recognize patterns with an imperfect teacher.

A decision rule for classifying patterns with an imperfect teacher is derived. Using nonparametric estimators for the unknown densities appearing in the decision rule, a procedure for learning to recognize patterns with an imperfect teacher is given. It is shown that the proposed learning scheme has an asymptotic average risk equal to the Bayes' minimum risk. For non-overlapping densities, the average asymptotic performance of the learning scheme is better than the teacher and nearest neighbor rule trained by the same imperfect teacher. The same is true for overlapping densities if the amount of overlap is less than $1 - \beta$, β being the probability that the teacher is correct. Also it is shown that for non-overlapping densities the proposed learning scheme performs better than the teacher, on the average, after looking a finite but large number of samples. The proposed learning scheme is simulated on the Computer for some simple density functions and the results are presented.

Introduction

A major step common to all pattern recognition problems consists of developing procedures which classify observations such that a particular strategy is optimized. This step can be formulated as follows. A set of n measurement pairs $(\underline{X}_1,\theta^1),\ldots,(\underline{X}_n,\theta^n)$ are given as sample (training) patterns. $\underline{X}_i (i=1,\ldots,n)$ is a vector measurement drawn from one of the R possible categories $\theta_1,\ldots\theta_R$. θ^i takes the form $\hat{\theta}_k$, when $\underline{X}_i$ is identified by the teacher as being from category $\hat{\theta}_k$. After development of a classification procedure, only the measurement $\underline{X}$ is available and an estimate is desired of the category from which $\underline{X}$ was drawn.

Depending on the nature of information available in the form of θ^i's, the problem of learning to recognize patterns can be subdivided into three classes. If θ^i contains identification of the true category of $\underline{X}_i$ then learning is said to take place with a "perfect teacher". If no information about the true category of $\underline{X}_i$ is available, then this class of problems is referred to as "learning without a teacher".

Between these two problems is the problem of "learning with an imperfect teacher". This problem has received much less attention; nevertheless, many situations fall into this category. For example, medical diagnoses which are used to determine the categories into which electrocardiogram records are to be classified are not perfect. The authors of this paper were led into an investigation of learning with an imperfect teacher by trying to classify sferics into cloud-to-cloud or cloud-to-ground discharges on the basis of measurements of electromagnetic signature. The categories for the training samples were identified by visual observations which apparently contained some errors.

This paper is concerned with developing procedures for learning to classify patterns with an imperfect teacher characterized by

$$P(\hat{\theta}_i|\theta_i) = \beta > \frac{1}{R}\ ; \qquad i = 1,\ldots,R$$

$$P(\hat{\theta}_j|\theta_i) = \left(\frac{1-\beta}{R-1}\right)\ ; \qquad i,j = 1,\ldots,R;\ i \neq j. \qquad (1.a)$$

The patterns are assumed to be probabilistic in nature with unknown conditional probability density functions $f_{\underline{X}|\theta_i}$, with the property that

$$f_{\underline{X}|\theta_i;\hat{\theta}_j} = f_{\underline{X}|\theta_i} \qquad i,j = 1,\ldots,R. \qquad (1.b)$$

A decision rule for classifying patterns with an imperfect teacher using discriminant functions of the form $P(\hat{\theta}_i)\, f_{\underline{X}|\hat{\theta}_i}$ is given. This decision rule is shown to be equivalent to a Bayes' decision rule using discriminant functions of the form $P(\theta_i)\, f_{\underline{X}|\theta_i}$. Nonparametric estimators $f_{\underline{X}|\hat{\theta}_i;n}$ of the unknown density $f_{\underline{X}|\hat{\theta}_i}$ are proposed for learning to recognize patterns with an imperfect teacher. Using one such estimator it is shown that the proposed learning scheme has an average asymptotic risk equal to the average Bayes' (minimum) risk. For non-overlapping densities and for densities with overlap less than $(1-\beta)$ it is shown that the average asymptotic performance of the learning scheme is better than that of the imperfect teacher and the nearest neighbor rule trained by the same imperfect teacher.

The performance of the learning scheme with a finite, but large number of samples is also derived for non-overlapping densities and it is shown that the learning scheme betters in probability the performance of the teacher after looking at a finite number of samples. A somewhat more surprising result is that more samples will be required to better the performance of either of the mediocre teacher. The proposed scheme was simulated on a computer to obtain the average risk for some simple density functions.

The Decision Rule

For probabilistic patterns with known probability distributions, a Bayes' procedure can be used to arrive at a decision rule that optimizes the given strategy. The strategy to be optimized is specified in terms of a loss function L_{ij}, defined for $i,j = 1,\ldots,R$. The loss function L_{ij} represents the loss incurred when a pattern actually belonging to category θ_j is misplaced into category θ_i. For a zero-one loss function L_{ij} =

$1-\delta_{ij}$, where δ_{ij} is the kronecker delta function, it has been shown[1] that the Bayes' procedure leads to discriminant functions of the form.

$$D_{\theta_i} = P(\theta_i)\, f_{\underline{X}|\theta_i} \qquad (2)$$

$P(\theta_i)$ is the prior probability of category θ_i and $f_{\underline{X}|\theta_i}$ is the probability density function of pattern $\underline{X}$ given that it belongs to θ_i. A given pattern $\underline{x}$ is classified into category θ_i if

$$D_{\theta_i}(\underline{x}) > D_{\theta_j}(\underline{x}) \qquad j = 1,\ldots,R;\ j \neq i \qquad (3)$$

It is assumed in Equation 2 that all information relevant to $P(\theta_i)$ and $f_{\underline{X}|\theta_i}$, $(i = 1,\ldots,R)$, were known. In practice, often this information is only partially known. The unknown information must be learned from the given set of labelled sample patterns, the information associated with D_{θ_i} being estimated from samples belonging to category θ_i. But due to the imperfect teacher, the true categories of the sample patterns are not available to the learning scheme. The only labeling information available to the student is one of $\hat{\theta}_1,\ldots,\hat{\theta}_R$ provided by the imperfect teacher. Hence in order to learn from these incorrectly labeled samples, it is necessary to derive a decision rule in terms of $P(\hat{\theta}_i)$ and $f_{\underline{X}|\hat{\theta}_i}$; $i = 1,\ldots,R$.

Theorem 1. With an imperfect teacher characterized by Equations (1.a) and (1.b), a decision rule using discriminant functions of the form $D_{\hat{\theta}_i} = P(\hat{\theta}_i)\, f_{\underline{X}|\hat{\theta}_i}$ is equivalent to a Bayes' decision rule using discriminant functions of the form $D_{\theta_i} = P(\theta_i)\, f_{\underline{X}|\theta_i}$.

Proof. The above theorem can be proved by showing that $D_{\hat{\theta}_i}(\underline{x}) \geq D_{\hat{\theta}_j}(\underline{x})$ if and only if $D_{\theta_i}(\underline{x}) \geq D_{\theta_j}(\underline{x})$; thus establishing that the two decision rules are equivalent.

Using Bayes' theorem it follows that the distribution function of $\underline{X}$ given that $\underline{X}$ is labelled as $\hat{\theta}_i$ is

$$F_{\underline{X}|\hat{\theta}_i}(\underline{x}|\hat{\theta}_i) = \sum_{k=1}^{R} F_{\underline{X}|\hat{\theta}_i,\theta_k}(\underline{x}|\hat{\theta}_i,\theta_k)P(\theta_k|\hat{\theta}_i)$$

Using the condition given in Equation (1.b) it follows that

$$F_{\underline{X}|\hat{\theta}_i}(\underline{x}|\hat{\theta}_i) = \sum_{k=1}^{R} F_{\underline{X}|\theta_k}(\underline{x}|\theta_k)P(\theta_k|\hat{\theta}_i)$$

$$= \sum_{k=1}^{R} F_{\underline{X}|\theta_k}(\underline{x}|\theta_k)\, \frac{P(\hat{\theta}_i|\theta_k)P(\theta_k)}{P(\hat{\theta}_i)}$$

$$F_{\underline{X}|\hat{\theta}_i}(\underline{x}|\hat{\theta}_i) = \frac{1}{P(\hat{\theta}_i)}\{P(\theta_i)\beta F_{\underline{X}|\theta_i}(\underline{x}|\theta_i) + \sum_{\substack{k=1\\k\neq i}}^{R} P(\theta_k)(\frac{1-\beta}{R-1})F_{\underline{X}|\theta_k}(\underline{x}|\theta_k)\}\ ,$$

and

$$f_{\underline{X}|\hat{\theta}_i}(\underline{x}|\hat{\theta}_i) = \frac{1}{P(\hat{\theta}_i)}\{P(\theta_i)\beta f_{\underline{X}|\theta_i}(\underline{x}|\theta_i) + \sum_{\substack{k=1\\k\neq i}}^{R} P(\theta_k)(\frac{1-\beta}{R-1})f_{\underline{X}|\theta_k}(\underline{x}|\theta_k)\}\ .$$

Hence

$$D_{\hat{\theta}_i}(\underline{x}) = P(\theta_i)\beta f_{\underline{X}|\theta_i}(\underline{x}|\theta_i) + \sum_{\substack{k=1\\k\neq i}}^{R} P(\theta_k)(\frac{1-\beta}{R-1})f_{\underline{X}|\theta_k}(\underline{x}|\theta_k)\ .$$

A similar expression can be obtained for $D_{\hat{\theta}_j}(\underline{x})$ and from these two equations it follows that

$$D_{\hat{\theta}_i}(\underline{x}) - D_{\hat{\theta}_j}(\underline{x}) = P(\theta_i)\beta f_{\underline{X}|\theta_i}(\underline{x}|\theta_i)$$
$$- P(\theta_j)\beta f_{\underline{X}|\theta_j}(\underline{x}|\theta_j)$$
$$+ P(\theta_j)(\frac{1-\beta}{R-1})f_{\underline{X}|\theta_j}(\underline{x}|\theta_j)$$
$$- P(\theta_i)(\frac{1-\beta}{R-1})f_{\underline{X}|\theta_i}(\underline{x}|\theta_i)$$
$$= (\frac{\beta R-1}{R-1})\{D_{\theta_i}(\underline{x}) - D_{\theta_j}(\underline{x})\}\ .$$

Since $\beta > \frac{1}{R}$ by assumption, it follows from the above equation that

$$D_{\hat{\theta}_i}(\underline{x}) \geq D_{\hat{\theta}_j}(\underline{x}) \Longleftrightarrow D_{\theta_i}(\underline{x}) \geq D_{\theta_j}(\underline{x})\ ,$$

as was to be shown.

If there are only two categories of patterns θ_1 and θ_2 and if $\beta > 1/2$, then classification can be done by evaluating a single discriminant function

$$D_{\hat{\theta}}(\underline{x}) = P(\hat{\theta}_1)\, f_{\underline{X}|\hat{\theta}_1}(\underline{x}) - P(\hat{\theta}_2)\, f_{\underline{X}|\hat{\theta}_2}(\underline{x})$$

$$= (2\beta-1)\,[P(\theta_1)\, f_{\underline{X}|\theta_1}(\underline{x}) - P(\theta_2)\, f_{\underline{X}|\theta_2}(\underline{x})]. \qquad (4)$$

A given pattern $\underline{x}$ is assigned to θ_1 if $D_{\hat{\theta}}(\underline{x}) > 0$ and θ_2 if $D_{\hat{\theta}}(\underline{x}) < 0$. From Equation (4) it can be seen that if $\beta < 1/2$, then changing the sign of $D_{\hat{\theta}}(\underline{x})$ will lead to an optimum classification procedure. Also it can be seen that when $\beta = 1/2$, no classification will result from the above discriminant function.

If the density functions $f_{\underline{X}|\theta_1}$ and if $f_{\underline{X}|\theta_2}$ do not overlap, then a discriminant function of the form

$$D'_{\hat{\theta}}(\underline{x}) = f_{\underline{X}|\hat{\theta}_1}(\underline{x}) - f_{\underline{X}|\hat{\theta}_2}(\underline{x}) \qquad (5)$$

is optimum for dichotomizing patterns. In fact,

$$f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1) - f_{\underline{X}|\hat{\theta}_2}(\underline{x}|\hat{\theta}_2) = \frac{1}{P(\hat{\theta}_1)}\{\beta P(\theta_1)f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)$$
$$+ (1-\beta)P(\theta_2)f_{\underline{X}|\theta_2}(\underline{x}|\theta_2)\}$$
$$- \frac{1}{P(\hat{\theta}_2)}\{(1-\beta)P(\theta_1)f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)$$
$$+ \beta P(\theta_2)f_{\underline{X}|\theta_2}(\underline{x}|\theta_2)\}$$

$$= \frac{1}{P(\hat{\theta}_1)P(\hat{\theta}_2)}\{P(\theta_1)f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)$$
$$[\beta P(\hat{\theta}_2) - (1-\beta)P(\hat{\theta}_1)]$$
$$- P(\theta_2)f_{\underline{X}|\theta_2}(\underline{x}|\theta_2)$$
$$[\beta P(\hat{\theta}_1) - (1-\beta)P(\hat{\theta}_2)]\}$$

$$= \frac{1}{P(\hat{\theta}_1)P(\hat{\theta}_2)}\{P(\theta_1)f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)[(2\beta-1)P(\theta_2)]$$
$$- P(\theta_2)f_{\underline{X}|\theta_2}(\underline{x}|\theta_2)[(2\beta-1)P(\theta_1)]\}$$

$$= \frac{P(\theta_1)P(\theta_2)}{P(\hat{\theta}_1)P(\hat{\theta}_2)} (2\beta - 1)\{f_{\underline{X}|\theta_1}(\underline{x}|\theta_1) - f_{\underline{X}|\theta_2}(\underline{x}|\theta_2)\}.$$

Hence

$$D'_{\hat{\theta}}(\underline{x}) = \frac{P(\theta_1)P(\theta_2)}{P(\hat{\theta}_1)P(\hat{\theta}_2)} (2\beta - 1)[f_{\underline{X}|\theta_1}(\underline{x}|\theta_1) - f_{\underline{X}|\theta_2}(\underline{x}|\theta_2)].$$

As in Equation (4) if $\beta < 1/2$, then $-D'_{\hat{\theta}}(\underline{x})$ instead of $D'_{\hat{\theta}}(\underline{x})$ can be used for classifying patterns.

Also, it can be seen from Equation (5) that $D'_{\hat{\theta}}(\underline{x})$ does not involve the exact value of β. The only information required is whether $\beta > 1/2$ or $\beta < 1/2$. The same is true of $D_{\hat{\theta}}(\underline{x})$, for overlapping densities.

Learning With An Imperfect Teacher

The decision rule derived in Theorem 1 involves $P(\hat{\theta}_i)$ and $f_{\underline{X}|\hat{\theta}_i}$; $i = 1,\ldots,R$. The samples are given with labels $\hat{\theta}_1,\ldots,\hat{\theta}_R$. Hence any unknown information associated with $D_{\hat{\theta}_i}$ can now be estimated (learned) through the samples carrying the label $\hat{\theta}_i$. In the remainder of this paper it will be assumed that $R = 2$, and that the prior probabilities $P(\hat{\theta}_1)$ and $P(\hat{\theta}_2)$ are known. (If unknown, $P(\hat{\theta}_1)$ and $P(\hat{\theta}_2)$ can be estimated by the number of times the labels $\hat{\theta}_1$ and $\hat{\theta}_2$ occur relative to the total number of samples used.)

The unknown densities $f_{\underline{X}|\hat{\theta}_1}$ and $f_{\underline{X}|\hat{\theta}_2}$ can be estimated from a set of incorrectly labeled independent sample patterns $\underline{X}_1,\ldots\underline{X}_{n_1};\underline{Y}_1,\ldots\underline{Y}_{n_2}$. The $\underline{X}_i$'s are sample patterns with labels $\hat{\theta}_1$ and are identically distributed random vectors with a common probability density function $f_{\underline{X}|\hat{\theta}_1}$. Similarly the $\underline{Y}_i$'s are patterns with labels $\hat{\theta}_2$ and identically distributed with a common probability density function $f_{\underline{X}|\hat{\theta}_2}$.

Using nonparametric estimators proposed and analyzed by Parzen[2] and Murthy[3], an estimate of $f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1)$ based on the sample patterns $\underline{X}_1,\ldots,\underline{X}_{n_1}$ is

$$\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) = \frac{1}{\sqrt{n_1}} \sum_{k=1}^{n_1} \frac{1}{(2\pi)^{\frac{p}{2}}} \left[\operatorname{Exp}\left\{\frac{-[\underline{x} - \underline{X}_k]^T[\underline{x} - \underline{X}_k](n_1)^{\frac{1}{p}}}{2}\right\}\right]. \quad (6)$$

and an estimate of $f_{\underline{X}|\theta_2}(\underline{x}|\theta_2)$ based on $\underline{Y}_1,\ldots,\underline{Y}_{n_2}$ is

$$\hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2) = \frac{1}{\sqrt{n_2}} \sum_{k=1}^{n_2} \frac{1}{(2\pi)^{\frac{p}{2}}} \left[\operatorname{Exp}\left\{\frac{-[\underline{x} - \underline{Y}_i]^T[\underline{x} - \underline{Y}_i](n_2)^{\frac{1}{p}}}{2}\right\}\right]. \quad (7)$$

In Equations (6) and (7) p is the dimension of the pattern space.

One of the disadvantages of this form of estimation is that all the sample patterns need to be stored. This difficulty can be overcome by using the polynomial approximation suggested by Specht (4) of the form.

$$\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) = \frac{1}{\sigma^p(2\pi)^{\frac{p}{2}}} [\operatorname{Exp} - (\frac{\underline{x}^T\underline{x}}{2\sigma^2})]\, D^{n_1}(\underline{x}). \quad (8)$$

In the above estimator, $D^{n_1}(\underline{x})$ is a polynomail with a finite number of terms whose coefficients are computed using the n_1 sample patterns labelled as $\hat{\theta}_1$. As additional samples become available, these coefficients can be updated through a recursive equation. Hence the sample patterns need not be stored permanently. One of the unsolved problems associated with Sprecht's method of estimation is the number of terms that one needs to include in the polynomial. For a desired accuracy, it may be feasible to derive a relationship involving the number of sample patterns the dimension of the pattern space and the unknown density function.

Under certain regularity conditions, the above mentioned estimators have been shown[2,3,4] to be consistent and asymptotically normally distributed. Using the estimated densities in the discriminant function given in Equation (4), the proposed learning scheme is:

(1) Using the incorrectly identified sample patterns, $\underline{X}_1,\ldots,\underline{X}_{n_1}$; $\underline{Y}_1,\ldots,\underline{Y}_{n_2}$, estimate $f_{\underline{X}|\hat{\theta}_1}$ and $f_{\underline{X}|\hat{\theta}_2}$;

(2) Using estimators $\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1)$ and $\hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2)$ compute

$$\hat{D}_{\hat{\theta}}(\underline{x}) = P(\hat{\theta}_1)\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) - P(\hat{\theta}_2)\hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2) \;;$$

(3) Assign $\underline{x}$ to

$$\theta_1 \text{ if } \hat{D}_{\hat{\theta}}(\underline{x}) > 0 \,,$$

and

$$\theta_2 \text{ if } \hat{D}_{\hat{\theta}}(\underline{x}) < 0 \,. \quad (9)$$

Performance of the Proposed Learning Scheme

Asymptotic Performance. The asymptotic performance of the proposed learning scheme can be analyzed using the consistency properties of the estimators $\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}$ and $\hat{f}_{\underline{X}|\hat{\theta}_2;n_2}$.

Theorem 2. The proposed learning scheme has an average asymptotic risk equal to the average Bayes risk.

Proof. It has been shown by Murthy[3] that $\hat{f}_{\underline{X}|\hat{\theta}_1;n_1} \longrightarrow f_{\underline{X}|\hat{\theta}_1}$ as $n_1 \longrightarrow \infty$ with Probability 1 and $\hat{f}_{\underline{X}|\hat{\theta}_2;n_2} \longrightarrow f_{\underline{X}|\hat{\theta}_2}$ as $n_2 \longrightarrow \infty$ with Probability 1. Hence with Probability one $\hat{D}_{\hat{\theta}} \longrightarrow D_{\hat{\theta}}$ as $n_1, n_2 \longrightarrow \infty$. Therefore with Probability one, the proposed learning scheme classifies a given pattern $\underline{x}$ into the same category into which a Bayes machine would place $\underline{x}$. Hence the conditional risk $r_s(\underline{x}; n_1, n_2)$ associated with classifying $\underline{x}$ according to (9), converges to the Bayes' conditional risk, $r^*(\underline{x})$, with Probability one, i.e $r_s(\underline{x}; n_1, n_2) \longrightarrow r^*(\underline{x})$ as $n_1, n_2 \longrightarrow \infty$ with Probability one. Hence

$$E\{r_s(\underline{x}; n_1, n_2)\} = r^*(\underline{x}) \text{ as } n_1, n_2 \longrightarrow \infty. \quad (10)$$

For a symmetrical loss function the Bayes' conditional risk is given by

$$r^*(\underline{x}) = \min\{P(\theta_1|\underline{x}) \,,\, P(\theta_2|\underline{x})\} \quad . \quad (11)$$

Taking the average on both sides of Equation (10) with respect to $f_{\underline{X}}(\underline{x})$, the average risk associated with learning with an imperfect teacher is

$$R_s = \int r^*(\underline{x})f_{\underline{X}}(\underline{x})d\underline{x}$$

$$= P(\theta_1) \int_{D_2} f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)d\underline{x}$$

$$+ P(\theta_2) \int_{D_1} f_{\underline{X}|\theta_2}(\underline{x}|\theta_2)d\underline{x} \quad (12)$$

where

$$D_1 = \{\underline{x} : P(\theta_1) f_{\underline{X}|\theta_1}(\underline{x}|\theta_1) > P(\theta_2) f_{\underline{X}|\theta_2}(\underline{x}|\theta_2)\}, \text{ and}$$

$$D_2 = \{\underline{x} : P(\theta_2) f_{\underline{X}|\theta_2}(\underline{x}|\theta_2) > P(\theta_1) f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)\} \quad .$$

The right hand side of Equation (12) is the Bayes' risk R^*, hence, as was to be shown,

$$R_s = R^* \qquad (13)$$

The average risk for the teacher denoted by R_t is

$$R_t = 1 - \beta \qquad (14)$$

and the average asymptotic risk for the nearest neighbor rule, R_n, has been shown [5] to be bounded by

$$(1 - \beta) + (2\beta - 1) R^* \leq R_n \leq$$

$$(1 - \beta) + (2\beta - 1)[2R^*(1 - R^*)] \qquad (15)$$

For non-overlapping densities $R^* = 0$ and from Equations (13), (14) and (15) it can be seen that the proposed learning scheme has a lower average risk and hence on the average performs better than the teacher and the nearest neighbor rule. Also if the overlap in densities is small, i.e. if $R^* < 1 - \beta$, then again the proposed learning scheme is better than the teacher and the nearest neighbor rule. In both cases the learning scheme (student) becomes smarter than the teacher.

<u>Large Sample Performance of the Learning Scheme</u>. In the previous sections of the asymptotic performance of the proposed learning scheme was analyzed and it was shown that if the density functions do not overlap then, on the average, the learning scheme performs better than the teacher. In this section it will be shown that the learning scheme performs better than the teacher, on the average, after being presented with a finite but large number of sample patterns $\underline{X}_1, \ldots, \underline{X}_{n_2}; \underline{Y}_1, \ldots, \underline{Y}_{n_2}$.

From Equation (5), the learning scheme for classifying patterns when the density functions do not overlap is:

$$\text{Assign } \underline{x} \text{ to } \theta_1 \text{ if } \hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) > \hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2) \qquad (16)$$

$$\text{Assign } \underline{x} \text{ to } \theta_2 \text{ if } \hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2) > \hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1). \qquad (17)$$

A given pattern $\underline{x}$ from category θ_1 is therefore classified correctly if (16) is satisfied and will be incorrectly if (17) holds. Assigning a value of +1 for correct classification and 0 for incorrect classification, the gain associated with classifying a pattern $\underline{x}$ form a category θ_1 is

$$g_s(\underline{x}|\theta_1;n_1,n_2) = P\{\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) > \hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2) | \underline{x}\epsilon\theta_1\} \qquad (18)$$

For estimators of the form given in Equations (6) and (7), Murthy[5] has shown that as $n_1, n_2 \to \infty$

$$E(|\hat{f}_{\underline{X}|\hat{\theta}_1;n_1} - f_{\underline{X}|\hat{\theta}_1}|^2) = \frac{1}{\sqrt{n_1}(2\sqrt{\pi})^P} f_{\underline{X}|\hat{\theta}_1} \qquad (19)$$

and

$$E(|\hat{f}_{\underline{X}|\hat{\theta}_2;n_2} - f_{\underline{X}|\hat{\theta}_2}|^2) = \frac{1}{\sqrt{n_2}(2\sqrt{\pi})^P} f_{\underline{X}|\hat{\theta}_2} \qquad (20)$$

These results can be used to derive a lower bound for $g_s(\underline{x}|\theta_1;n_1, n_2)$.

<u>Theorem 3</u>. If (19) and (20) holds, then as n_1 and $n_2 \to \infty$, for $\underline{x}$ from category θ_1

$$P\{\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) > \hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2)|\underline{x}\epsilon\theta_1\} \geq L(\beta,n_1,n_2,\underline{x})$$

where

$$L(\beta,n_1,n,\underline{x}) = [1 - \frac{C_1\beta}{\sqrt{n_1}\, f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)}]$$

$$\times [1 - \frac{C_2(1 - \beta)}{\sqrt{n_2}\, f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)}] \qquad (21)$$

and

$$C_1 = \frac{P(\theta_1)}{P(\hat{\theta}_1)} [\frac{P(\hat{\theta}_1)P(\hat{\theta}_2)}{P(\theta_1)P(\theta_2)(2\beta - 1)}]^2 \frac{4}{(2\sqrt{\pi})^P}$$

$$C_2 = \frac{P(\theta_1)}{P(\hat{\theta}_2)} [\frac{P(\hat{\theta}_1)P(\hat{\theta}_2)}{P(\theta_1)P(\theta_2)(2\beta - 1)}]^2 \frac{4}{(2\sqrt{\pi})^P} \qquad (22)$$

<u>Proof</u>. Let

$$D = f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1) - f_{\underline{X}|\hat{\theta}_2}(\underline{x}|\hat{\theta}_2) > 0$$

and let

$$D_1 = \{\underline{x}: f_{\underline{X}|\theta_1}(\underline{x}|\theta_1) > 0\} \quad .$$

$$P\{\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) > \hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2)|\underline{x}\epsilon\theta_1\}$$

$$\geq P\{|\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) - f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1)| > \frac{D}{2} \bigcap$$

$$|\hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2) - f_{\underline{X}|\hat{\theta}_2}(\underline{x}|\hat{\theta}_2)| < \frac{D}{2} \mid \underline{x}\epsilon\theta_1\} .$$

Since the estimators $\hat{f}_{X|\hat{\theta}_1;n_1}$ and $\hat{f}_{X|\hat{\theta}_2;n_2}$ are independent, the right hand side of the inequality becomes

$$\geq P\{|\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) - f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1)| < \frac{D}{2} \mid \underline{x}\epsilon\theta_1\}$$

$$P\{|\hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2) - f_{\underline{X}|\hat{\theta}_2}(\underline{x}|\hat{\theta}_2)| < \frac{D}{2} \mid \underline{x}\epsilon\theta_1\}$$

$$\geq P\{|\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) - f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1)|^2 < \frac{D^2}{4} \mid \underline{x}\epsilon\theta_1\}$$

$$P\{|\hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2) - f_{\underline{X}|\hat{\theta}_2}(\underline{x}|\hat{\theta}_2)|^2 < \frac{D^2}{4} \mid \underline{x}\epsilon\theta_1\}. \qquad (23)$$

Let us consider

$$P\{|\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) - f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1)|^2 < \frac{D^2}{4}\}$$

$$= 1 - P\{|\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) - f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1)|^2 > \frac{D^2}{4}\}$$

$$\geq 1 - \frac{E(|\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) - f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1)|^2)}{\frac{D^2}{4}} \qquad (24)$$

by Chebyshev's inequality. From Equation (19)

$$E(|\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) - f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1)|^2)$$

$$= \frac{1}{\sqrt{n_1}(2\sqrt{\pi})^p} f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1) \qquad (25)$$

Substituting (25) in (24), the right hand side of (24) becomes

$$\geq [1 - \frac{f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1)}{\sqrt{n_1}\,(2\sqrt{\pi})^p} \cdot \frac{4}{D^2}] \quad . \qquad (26)$$

Similarly

$$P(|f_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2) - f_{\underline{X}|\hat{\theta}_2}(\underline{x}|\hat{\theta}_2)|^2 < \frac{D^2}{4})$$

$$\geq [1 - \frac{f_{\underline{X}|\hat{\theta}_2}(\underline{x}|\hat{\theta}_2)}{\sqrt{n_2}\,(2\sqrt{\pi})^p} \cdot \frac{4}{D^2}] \quad . \qquad (27)$$

If $\underline{x}\epsilon\theta_1$ then $\underline{x}\epsilon D_1$, and on D_1

$$f_{\underline{X}|\hat{\theta}_1}(\underline{x}|\hat{\theta}_1) = \beta \frac{P(\theta_1)}{P(\hat{\theta}_1)} f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)$$

$$f_{\underline{X}|\hat{\theta}_2}(\underline{x}|\hat{\theta}_2) = (1 - \beta) \frac{P(\theta_1)}{P(\hat{\theta}_2)} f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)$$

and

$$D = \frac{P(\theta_1)P(\theta_2)}{P(\hat{\theta}_1)P(\hat{\theta}_2)} (2\beta - 1) f_{\underline{X}|\theta_1}(\underline{x}|\theta_1) \quad . \qquad (28)$$

Substituting (26), (27) and (28) in (23), one obtains

$$P(\hat{f}_{\underline{X}|\hat{\theta}_1;n_1}(\underline{x}|\hat{\theta}_1) > \hat{f}_{\underline{X}|\hat{\theta}_2;n_2}(\underline{x}|\hat{\theta}_2)|\underline{x}\epsilon\theta_1) \geq$$

$$[1 - \frac{C_1\beta}{\sqrt{n_1}\, f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)}][1 - \frac{C_2(1 - \beta)}{\sqrt{n_2}\, f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)}]$$

where

$$C_1 = \frac{P(\theta_1)}{P(\hat{\theta}_1)} [\frac{P(\hat{\theta}_1)P(\hat{\theta}_2)}{P(\theta_1)P(\theta_2)(2\beta - 1)}]^2 \frac{4}{(2\sqrt{\pi})^p}$$

$$C_2 = \frac{P(\theta_1)}{P(\hat{\theta}_2)} [\frac{P(\hat{\theta}_1)P(\hat{\theta}_2)}{P(\theta_1)P(\theta_2)(2\beta - 1)}]^2 \frac{4}{(2\sqrt{\pi})^p}$$

and hence the proof of the theorem.

Substituting the results of Theorem 3 in Equation (18), the gain of the learning system associated with classifying a pattern $\underline{x}$ from category θ_1 becomes

$$g_s(\underline{x}|\theta_1;n_1,n_2) \geq [1 - \frac{C_1\beta}{\sqrt{n_1}\, f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)}]$$

$$\times [1 - \frac{C_2(1 - \beta)}{\sqrt{n_2}\, f_{\underline{X}|\theta_2}(\underline{x}|\theta_2)}] \quad .$$

A similar expression can be derived for the gain associated with classifying a sample $\underline{x}$ from category θ_2. The gain of the teacher for classifying $\underline{x}$ from category θ_1 is

$$g_t(\underline{x}|\theta_1) = \beta$$

By setting

$$[1 - \frac{C_1\beta}{\sqrt{n_1}\, f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)}][1 - \frac{C_2(1 - \beta)}{\sqrt{n_2}\, f_{\underline{X}|\theta_1}(\underline{x}|\theta_1)}] > \beta \; ,$$

one can solve for n_1 and n_2, the sample size required by the learning scheme to better the performance of the teacher. Hence the justification for the claim that, in the case of non-overlapping densities, the learning scheme performs better than the teacher on the average after looking at a finite but large number of sample patterns.

The sample size required by the learning scheme to better the performance of the teacher is given below in Table I. The densities used in these sample calculations are assumed to be uniformly distributed over non-overlapping intervals of unit length, with $P(\theta_1) = P(\theta_2) = 1/2$.

TABLE I

SAMPLE SIZE REQUIRED BY THE LEARNING SCHEME TO PERFORM BETTER THAN THE TEACHER

β	0.60	0.70	0.80	0.90	0.95
Approximate Sample Size n_1+n_2	5000	1800	500	300	1600

A rather surprising inference that can be derived from this example is that the learning scheme requires less samples to better the performance of a mediocre teacher than the number of samples it requires to better either a very bad or a very good teacher, i.e. it is easier to better a mediocre teacher.

By differentiating with respect to β it can be shown[6] that the gain increases as β increases, thus showing that the knowledge acquired at a given stage of learning is greater with a better teacher.

SIMULATIONS

The proposed learning scheme was simulated on the IBM-360 computer for both overlapping and non-overlapping density functions. The various density functions used in the simulations are shown in Figures 1 and 2. The prior probabilities for the categories were set equal to 1/2. For each value of β, the densities were estimated using 75 and 100 samples ($n_1+n_2 = 75,100$). The risk for the learning scheme was calculated based on the classification of fifty test samples, the loss function being +1 for incorrect classification and 0 for correct classification. For each value of β, ten runs were made and the average risk for the learning scheme was calculated. The results of the simulations are shown in Figures 3 and 4.

Figure 3 shows the plot of average risk versus β for the learning scheme for non-overlapping densities shown in Figure 1. The Bayes' risk R^* for non-overlapping densities is zero and the average risk for the imperfect teacher is $(1 - \beta)$. Figure 4 shows the same plot for overlapping densities shown in Figure 2. The Bayes' risk now is 0.125 and the average risk for the

teacher is $(1 - \beta)$

From Figures 3 and 4 the following theoretical results can be verified:

(1) The average asymptotic risk for the learning scheme converges to the Bayes' risk.

(2) For non-overlapping densities the learning scheme betters the imperfect teacher, and the Nearest Neighbor Rule after looking at a finite number of sample patterns.

(3) For overlapping densities, the learning scheme is better than the teacher if $R^* < 1 - \beta$. In Figure 4, th s corresponds to $\beta < 0.875$.

(4) For a given number of training samples, the average risk decreases as β increases.

It must be pointed out here that the plots represent only the "average" performance of the learning system. On any given set of samples the performance of the learning scheme will depend on the number of correctly labeled samples. If a particular sequence of sample patterns had too many incorrect labels, then the performance of the learning scheme will be worse than the "average" performance.

Conclusions

A scheme for learning to recognize patterns with an imperfect teacher has been proposed. The proposed learning scheme makes use of patterns incorrectly labeled by the imperfect teacher. The only knowledge about the teacher that is needed is whether β (β is the probability that the teacher labels a sample correctly) is greater than or less than 1/2. Using Sprecht's approximation, it is possible to make the learning take place serially. The proposed learning scheme has an average asymptotic risk equal to the Bayes' (minimum) risk. If the density functions involved do not overlap, then the proposed learning scheme performs better than the imperfect teacher and the single nearest neighbor rule using the same sample patterns. With overlapping density functions, if the amount of overlap is less than $(1 - \beta)$, the average asymptotic performance of the proposed learning scheme is still better than that of the teacher and the nearest neighbor rule.

Acknowledgements

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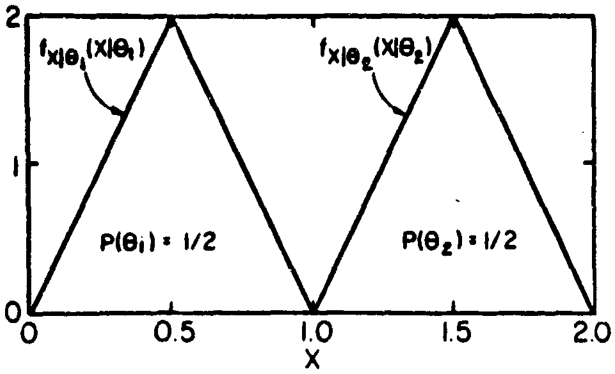

Figure 1. Non-overlapping Densities Used in Simulation

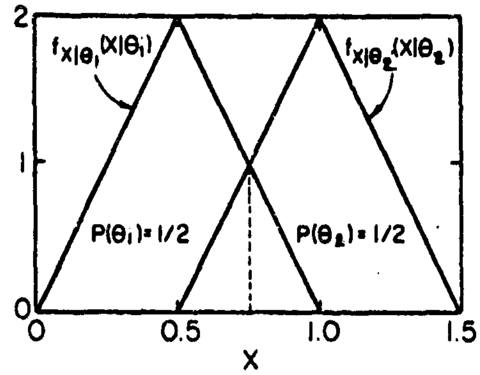

Figure 2. Overlapping Densities Used in Simulations

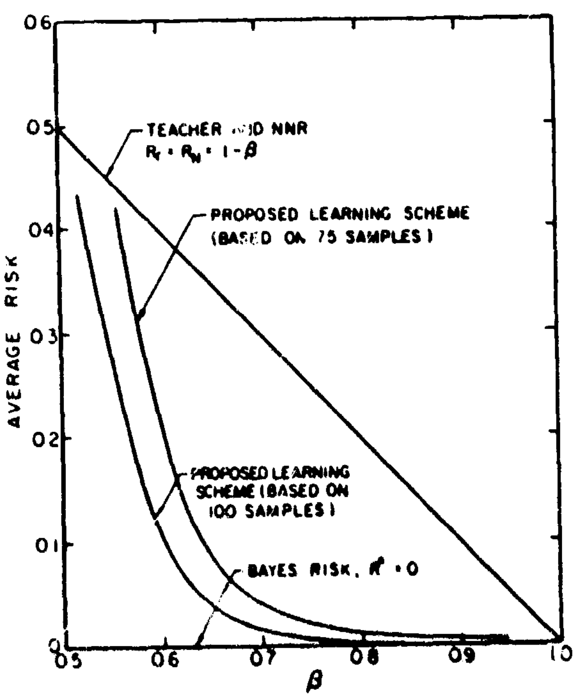

Figure 3. Average Risk vs β for non-overlapping densities.

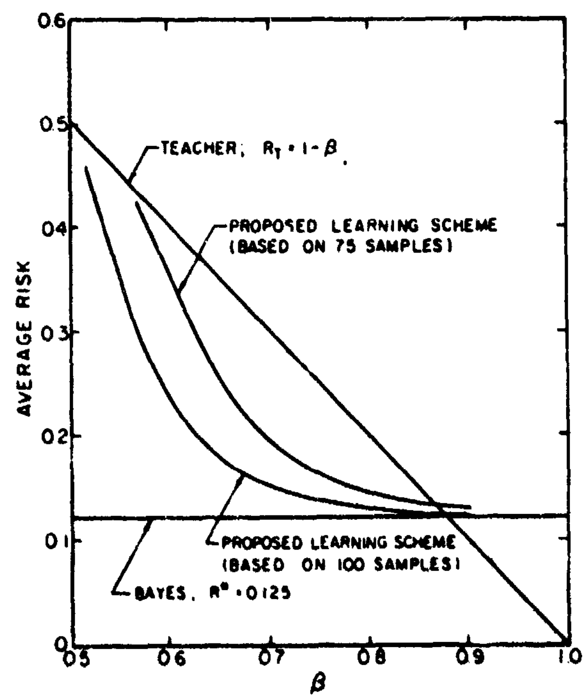

Figure 4. Average Risk vs β for overlapping densities.

AN ERROR CORRECTING PROCEDURE FOR LEARNING WITH AN IMPERFECT TEACHER

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ABSTRACT

Supervised learning in pattern recognition problems takes place through the use of a set of labeled sample patterns, the labels being provided by a "teacher". In most of the procedures for learning with a teacher, it is commonly assumed that the teacher is perfect, i.e. the labels of the sample patterns are always correct. However, there are many circumstances in which the patterns used for learning are occasionally mislabeled. This paper is concerned with developing a procedure for learning with an imperfect teacher, who occasionally mislabels some of the learning patterns.

The proposed error correction scheme is based on a nonparametric learning scheme. The error correction consists of questioning and correcting the labels provided by the imperfect teacher, using a threshold in the correction scheme. The use of threshold facilitates control over the amount of correction and provides a simple method for combining the knowledge acquired by the learning scheme with that provided by the teacher. Expressions for the threshold are derived and the properties of the proposed error correction scheme are discussed. Through computer simulations, the performance of the proposed error correction scheme is compared with that of an identical learning scheme without error correction.

I. INTRODUCTION

The problem of learning with an imperfect teacher investigated in this paper consists of the following. A set of n measurement pairs $(X_1,\theta^1),\ldots,(X_n,\theta^n)$ are given as learning observations. $X_i,(i = 1,\ldots n)$ is a vector measurement drawn from one of the two possible categories θ_1, θ_2. The label $\theta^i(i = 1,\ldots,n)$ takes the form $\hat{\theta}_1$ or $\hat{\theta}_2$ depending whether the teacher identifies X_i as coming from category θ_1 or θ_2 respectively. Based on this set of incorrectly labeled learning observations, we want to learn to classify new observations into θ_1 or θ_2 with minimum probability of misclassification.

The imperfect teacher provides the labels on the sample patterns according to the following probabilities.

$$P(\hat{\theta}_i|\theta_i) = \beta > 1/2 \qquad i = 1,2$$

$$P(\hat{\theta}_j|\theta_i) = 1-\beta \qquad i, j = 1,2; \; i \neq j \tag{1}$$

The patterns are probabilistic in nature with unknown conditional probability density functions $f_{X|\theta_1}$ and $f_{X|\theta_2}$. No particular functional form for these density functions will be assumed. However, it will be assumed that the density functions have disjoint supports. Also it is assumed that

$$f_{X|\theta_i,\hat{\theta}_j} = f_{X|\theta_i} \qquad i, j = 1,2. \tag{2}$$

Many of the procedures for learning with a perfect teacher have been investigated for use with an imperfect teacher [1,2]. R. O. Duda and R. C. Singleton [3] investigated the performance of a threshold logic unit trained with an imperfect teacher. They have shown that for

orthogonal patterns, the average weight vector converges to a solution vector for the correctly labeled pattern set. A. W. Whitney and S. J. Dwyer III [4] analyzed the performance of the k-nearest neighbor rule with an imperfect teacher and obtained error bounds for the performance. The problem of learning without a teacher has been formulated as learning with an imperfect (probabilistic) teacher and a Bayesian reproducing estimation procedure has been developed for this problem by A. K. Agrawala [5].

The authors of this investigation have proposed [6] a nonparametric scheme for learning with an imperfect teacher, which asymptotically performs better than its own imperfect teacher. Since the learning scheme becomes better than the teacher, the authors were motivated towards using the learning scheme's own knowledge to correct the errors in the labels provided by the teacher. The result is an error correcting scheme for learning with an imperfect teacher. The proposed scheme uses a threshold in the correction loop. The use of threshold provides control over the amount of correction and also provides a simple way for combining the learning scheme's knowledge with the knowledge of its teacher. Also the use of threshold facilitates a gradual phasing out of the teacher as the learning scheme acquires more and more knowledge. Expressions for the threshold are derived and the properties of the learning scheme are discussed. Through computer simulations, the performance of the error correcting scheme is compared with the performance of an identical learning scheme using no error correction.

II. LEARNING WITH AN IMPERFECT TEACHER

For nonoverlapping densities $f_{X|\theta_1}$ and $f_{X|\theta_2}$, a discriminant function of the form

$$D_\theta(X) = f_{X|\theta_1} - f_{X|\theta_2} \tag{3}$$

can be used to classify a pattern X into θ_1 or θ_2 with a probability of misclassification equal to zero. The unknown density functions $f_{X|\theta_i}$ can be learned (estimated) from the sample patterns which belong to category θ_i. However, due to the randomness of the labeling of the teacher, the true categories of the sample patterns are not known. The only labeling information available is one of $\hat{\theta}_1$ or $\hat{\theta}_2$. In order to learn to recognize patterns from these incorrectly labeled samples, it is necessary to have a decision rule in terms of $f_{X|\hat{\theta}_1}$ and $f_{X|\hat{\theta}_2}$ rather than in terms of $f_{X|\theta_1}$ and $f_{X|\theta_2}$.

With an imperfect teacher characterized by Equation (1) and with non-overlapping densities, the discriminant function

$$D_{\hat{\theta}}(X) = f_{X|\hat{\theta}_1} - f_{X|\hat{\theta}_2} \tag{4}$$

is equivalent to the discriminant function $D_\theta(X)$ defined in Equation (3). In fact, it can be shown [6] that

$$f_{X|\hat{\theta}_1} = \frac{1}{P(\hat{\theta}_1)} (\beta P(\theta_1)\, f_{X|\theta_1} + (1-\beta)P(\theta_2)\, f_{X|\theta_2}) \tag{5}$$

$$f_{X|\hat{\theta}_2} = \frac{1}{P(\hat{\theta}_2)} ((1-\beta)P(\theta_1)\, f_{X|\theta_1} + \beta P(\theta_2)\, f_{X|\theta_2}) \tag{6}$$

and hence

$$D_{\hat{\theta}}(X) = \frac{P(\theta_1)\,P(\theta_2)}{P(\hat{\theta}_1)\,P(\hat{\theta}_2)}\,(2\beta-1)D_\theta(X). \tag{7}$$

Since $\beta > 1/2$, Equation (7) implies that

$$D_{\hat{\theta}}(X) \geq 0 \iff D_\theta(X) \geq 0$$

and hence the equivalence of the two discriminant functions.

The unknown density functions in the discriminant function $D_{\hat{\theta}}(X)$ are $f_{X|\hat{\theta}_1}$ and $f_{X|\hat{\theta}_2}$ and these can be estimated from the given set of sample patterns carrying labels $\hat{\theta}_1$ and $\hat{\theta}_2$ respectively. Using nonparametric estimators proposed and analyzed by Parzen [7] and Murthy [8], an estimate of $f_{X|\hat{\theta}_1}(x|\hat{\theta}_1)$ based on the sample patterns $X_1,\ldots,X_{n_1}$ labeled as $\hat{\theta}_1$ is

$$\hat{f}_{X|\hat{\theta}_1;n_1}(x|\hat{\theta}_1) = \frac{1}{\sqrt{n_1}} \sum_{k=1}^{n_1} \frac{1}{(2\pi)^{\frac{p}{2}}} \operatorname{Exp}\left\{\frac{-[x - X_k]^T[x - X_k](n_1)^{\frac{1}{p}}}{2}\right\} . \tag{8}$$

and an estimate of $f_{X|\hat{\theta}_2}(x|\hat{\theta}_2)$ based on the sample patterns $Y_1,\ldots,Y_{n_2}$ labeled as $\hat{\theta}_2$ is

$$\hat{f}_{X|\hat{\theta}_2;n_2}(x|\hat{\theta}_2) = \frac{1}{\sqrt{n_2}} \sum_{i=1}^{n_2} \frac{1}{(2\pi)^{\frac{p}{2}}} \operatorname{Exp}\left\{\frac{-[x - Y_i]^T[x - Y_i](n_2)^{\frac{1}{p}}}{2}\right\} . \tag{9}$$

In Equations (8) and (9) p is the dimension of the pattern space and T indicates transpose. A multivariate normal density function was chosen as a kernel in the estimators since this would facilitate the use of a polynomial approximation suggested by Specht [9]. The polynomial approximation to the estimators is easy to implement on the computer and results in an appreciable reduction in the storage requirements.

Substituting the estimated densities in Equation (4), a procedure for learning to recognize patterns using a set of incorrectly labeled

patterns is:

(1) From the given set of labeled patterns, estimate $f_{X|\hat{\theta}_1}$ and $f_{X|\hat{\theta}_2}$ according to Equations (8) and (9).

(2) Using the estimated density functions, compute

$$\hat{D}_{\hat{\theta}}(X) = \hat{f}_{X|\hat{\theta}_1;n_1} - \hat{f}_{X|\hat{\theta}_2;n_2}$$

(3) Assign X to

$$\theta_1 \text{ if } \hat{D}_{\hat{\theta}}(X) > 0$$

and to

$$\theta_2 \text{ if } \hat{D}_{\hat{\theta}}(X) < 0 \tag{10}$$

Under certain regularity conditions, the estimates given in Equations (8) and (9) have been shown to be consistent and asymptotically normally distributed [7,8]. As a consequence of the consistency properties of the estimators it follows that, with probability one

$$\hat{D}_{\hat{\theta}}(X) = \hat{f}_{X|\hat{\theta}_1;n_1} - \hat{f}_{X|\hat{\theta}_2;n_2} \rightarrow D_{\hat{\theta}}(X) \quad \text{as } n_1,\ n_2 \rightarrow \infty\ .$$

Hence in the asymptotic case, the proposed learning scheme places a pattern X into the same category as a scheme using a Bayes procedure, with probability one. For a loss function of +1 for misclassification and 0 for correct classification, the average asymptotic risk for the learning scheme is zero. The average risk for the teacher is $1-\beta > 0$. Hence the proposed learning scheme is better than the teacher in the asymptotic case.

Since the learning scheme performs better than its teacher after looking at a large number of samples, the knowledge gained by the learning scheme might be used to verify and perhaps correct the label provided

by the teacher. Such corrections, if done successfully, could result in a lesser number of incorrect labels on the learning observations and hence lead to better performance. The remainder of this paper is devoted to developing such an error correcting procedure.

III. ERROR CORRECTION

Model:

The authors' motivation for considering an error correcting learning procedure comes from an example that is of common occurrence in classrooms. Such an example is the attempt of a student to question and possibly correct errors made by his teacher. In spite of the fact that much of the student's knowledge is derived from his teacher, he is still able to use this knowledge to occasionally correct his teacher and also provide answers to certain questions for which his teacher may not know the correct answer. Hence it seems that such questioning and possibly correcting the labeling information supplied by the teacher in pattern recognition problems is all too relevant especially if the teacher is known to be imperfect.

The model for our error correcting scheme is shown in Figure 1. The block marked student is the learning scheme described in the previous section, capable of learning from a set of labeled sample patterns. The teacher is characterized probabilistically in Equation (1). When a sample observation X is presented, the student provides a label for the observation based on his present knowledge (i.e. based on the latest estimate $\hat{D}_{\hat{\theta}}$ of the discriminant function $D_{\hat{\theta}}$). The label provided by the student is $\hat{\theta}_1$ if $\hat{D}_{\hat{\theta}}(X) \geq 0$ and $\hat{\theta}_2$ if $\hat{D}_{\hat{\theta}}(X) < 0$. The teacher also provides a label for X according to Equation (1). We propose that the error correction scheme compare these two labels and change the label provided by the teacher according to the following algorithm:

(1) Accept the label provided by the teacher if

$$|D_{\hat{\theta}}(X)| = |\hat{f}_{X|\hat{\theta}_1;n_1}(X|\hat{\theta}_1) - \hat{f}_{X|\hat{\theta}_2;n_2}(X|\hat{\theta}_2)| \leq T$$

(2) Change the label provided by the teacher to $\hat{\theta}_1$ if

$$\hat{f}_{X|\hat{\theta}_1;n_1}(X|\hat{\theta}_1) > \hat{f}_{X|\hat{\theta}_2;n_2}(X|\hat{\theta}_2) + T$$

(3) Change the label provided by the teacher to $\hat{\theta}_2$ if

$$\hat{f}_{X|\hat{\theta}_2;n_2}(X|\hat{\theta}_2) > \hat{f}_{X|\hat{\theta}_1;n_1}(X|\hat{\theta}_1) + T. \tag{11}$$

In the above algorithm n_1 and n_2 are the number of sample observations that have been used in the estimators of $f_{X|\hat{\theta}_1}$ and $f_{X|\hat{\theta}_2}$, respectively, and T is a threshold. After the label is decided, X is used to update the estimate of the density function corresponding to that label.

According to the above algorithm, a correction takes place only if the estimators of the density functions differ by more than T. Loosely stated, the label provided by the teacher is questioned and changed only if the student is "certain" that the teacher is wrong. The student accepts whatever the teacher says if he is not sure of himself.

The extent to which the student depends on his teacher during the learning process is determined by T. Two special cases occur when $T = 0$ or $T \to \infty$. If $T \to \infty$, then from the first step in algorithm (11) it follows that the label provided by the teacher is always accepted. If $T = 0$, then it can be seen that the student completely ignores his teacher and provides his own label for each sample pattern. By choosing a variable threshold, the dependancy of the student on his teacher can be controlled during the learning process.

Selection of Threshold:

Two methods will be presented for selecting a value for the threshold T. These methods are based on the asymptotic normality of the estimators of the density functions. To simplify the following treatment, the sample sizes n_1, n_2 will be assumed equal to a common value n, the value of n being large enough to justify the use of the asymptotic properties of the estimators. From the results of Murthy [8], the estimators given in Equations (8) and (9) have the following asymptotic distributions.

$$\hat{f}_{X|\hat{\theta}_1;n}(x|\hat{\theta}_1) \sim N\left(f_{X|\hat{\theta}_1}(x|\hat{\theta}_1),\ \frac{f_{X|\hat{\theta}_1}(x|\hat{\theta}_1)}{\sqrt{n}\ (2\ \sqrt{\pi})^p}\right)$$

$$\hat{f}_{X|\hat{\theta}_2;n}(x|\hat{\theta}_2) \sim N\left(f_{X|\hat{\theta}_2}(x|\hat{\theta}_2),\ \frac{f_{X|\hat{\theta}_2}(x|\hat{\theta}_2)}{\sqrt{n}\ (2\ \sqrt{\pi})^p}\right) . \tag{12}$$

The estimators are independent because of the assumption of independent samples, and hence

$$\hat{f}_{X|\hat{\theta}_1;n}(x|\hat{\theta}_1) - \hat{f}_{X|\hat{\theta}_2;n}(x|\hat{\theta}_2) \sim N\left(f_{X|\hat{\theta}_1}(x|\hat{\theta}_1) - f_{X|\hat{\theta}_2}(x|\hat{\theta}_2),\ \frac{f_{X|\hat{\theta}_1}(x|\hat{\theta}_1) + f_{X|\hat{\theta}_2}(x|\hat{\theta}_2)}{\sqrt{n}\ (2\ \sqrt{\pi})^p}\right). \tag{13}$$

If $x \varepsilon \theta_1$, then $f_{X|\theta_2}(x|\theta_2) = 0$, and from Equations (5) and (6),

$$f_{X|\hat{\theta}_1}(x|\hat{\theta}_1) = \beta f_{X|\theta_1}(x|\theta_1) \text{ and } f_{X|\hat{\theta}_2}(x|\hat{\theta}_2) = (1-\beta)\ f_{X|\theta_1}(x|\theta_1) .$$

Hence, if $x \varepsilon \theta_1$,

$$\hat{f}_{X|\hat{\theta}_1;n}(x|\hat{\theta}_1) \quad \hat{f}_{X|\hat{\theta}_2;n}(x|\hat{\theta}_2) \sim N\left((2\beta-1)\ f_{X|\theta_1}(x|\theta_1),\frac{f_{X|\theta_1}(x|\theta_1)}{\sqrt{n}\ (2\ \sqrt{\pi})^p}\right). \tag{14}$$

If $x \epsilon \theta_2$, then $f_{X|\theta_1}(x|\theta_1) = 0$, and from Equations (5) and (6),

$$f_{X|\hat{\theta}_1}(x|\hat{\theta}_1) = (1-\beta)\, f_{X|\theta_2}(x|\theta_2) \text{ and } f_{X|\hat{\theta}_2}(x|\hat{\theta}_2) = \beta f_{X|\theta_2}(x|\theta_2).$$

Hence, if $x \epsilon \theta_2$,

$$\hat{f}_{X|\hat{\theta}_1;n}(x|\hat{\theta}_1) - \hat{f}_{X|\hat{\theta}_2;n}(x|\hat{\theta}_2) \sim N\left(-(2\beta-1)\, f_{X|\theta_2}(x|\theta_2), \frac{f_{X|\theta_2}(x|\theta_2)}{\sqrt{n}\,(2\sqrt{\pi})^P}\right). \quad (15)$$

The approximations given in Equations (13), (14) and (15) will be used in deriving expressions for the threshold T. Also the notation P_n (accept the label), P_n (good label) and P_n (bad label) will be used to denote respectively the probabilities that the student accepted the label provided by the teacher, the probability that the student provided a correct label for the sample pattern, and the probability that the student provided an incorrect label for the sample pattern. The subscript n denotes that label provided by the student is based on the estimators of the density functions using sample size n.

The first approach to be discussed for selection of T is based on a minimax principle. In this rather pessimistic approach, T is selected by setting a bound on the maximum probability of a bad label by the student. Hence the quantity of interest is the probability of a bad label by the student. Let us first look at P_n (bad label $|x\epsilon\theta_1$), given by

$$P_n \text{ (bad label } |x\epsilon\theta_1) = P\{\hat{f}_{X|\hat{\theta}_2;n}(x|\hat{\theta}_2) > \hat{f}_{X|\hat{\theta}_1;n}(x|\hat{\theta}_1) + T|x\epsilon\theta_1\}.$$

From Equation (14), the right hand side of the above equation becomes

$$= \int_{-\infty}^{-T} N\left((2\beta-1)\, f_{X|\theta_1}(x|\theta_1), \frac{f_{X|\theta_1}(x|\theta_1)}{\sqrt{n}\,(2\sqrt{\pi})^P}\right) d\xi \quad ,$$

where the notation $\int_a^b N(\mu, \sigma^2)d\xi$ denotes the integral

$$\int_a^b \frac{1}{\sqrt{2\pi\sigma^2}} \exp\{-\frac{1}{2}\frac{(\xi-\mu)^2}{\sigma^2}\}d\xi \ .$$

A change of variable in the above integral gives P_n (bad label $|x\varepsilon\theta_1$) =

$$\int_{-\infty}^{\frac{[-T-(2\beta-1)a]c}{\sqrt{a}} = L} N(0, 1)d\xi \ , \tag{16}$$

where

$$c = (2\sqrt{\pi})^{\frac{p}{2}} n^{\frac{1}{4}} \text{ and } a = f_{X|\theta_1}(x|\theta_1).$$

It can be shown that L has a maximum at,

$$a = \frac{T}{(2\beta-1)} \ .$$

This implies P_n (bad label $|x\varepsilon\theta_1$) is maximum at

$$a = f_{X|\theta_1}(x|\theta_1) = \frac{T}{(2\beta-1)} \ .$$

Substituting $a = \frac{T}{(2\beta-1)}$ in Equation (16), the maximum value of P_n (bad label $|x\varepsilon\theta_1$) becomes

$$\int_{-\infty}^{-\frac{2T}{[T/(2\beta-1)]^{1/2}}c = -2c\sqrt{T(2\beta-1)}} N(0, 1)d\xi \tag{17}$$

Similarly the maximum value of P_n (bad label $|x\varepsilon\theta_2$) can also be shown to be equal to the integral in Equation (17). Hence irrespective of whether $x\varepsilon\theta_1$ or θ_2, the maximum probability of a bad label is given by the integral in Equation (17). If α is the desired limit on the maximum

probability of bad label, then a value t_α can be determined such that

$$\alpha = \int_{-\infty}^{-t_\alpha} N\ (0,\ 1)d\xi \tag{18}$$

Comparing the upper limits of the integrals in Equations (17) and (18),

$$2T^{1/2}c(2\beta-1)^{1/2} = t_\alpha$$

Solving for T from the above Equation,

$$T = \frac{c_\alpha}{\sqrt{n}\ (2\beta-1)}\ , \tag{19}$$

where

$$c_\alpha = \frac{t_\alpha^2}{4(2\sqrt{\pi})^p}\ .$$

Choosing T according to Equation (19) guarantees that on the average the maximum value of the probability that the student provides a bad label at any given stage of learning is equal to the desired value . For any given pattern x the probability of bad label is less than or equal to α. The choice of α and hence t_α is subjective.

The second method for selecting the threshold T is based on a decision theory approach. In this approach, values are assigned to the possible outcome of error correction and T is chosen such that the "expected value" is maximized. The two main outcomes of the error correction scheme are that the teacher's label is accepted or the student provides a label. There are two outcomes associated with the student providing a label, namely the label provided by the student is correct and label provided by the student is incorrect. Let us assign the values 0, a' and b' respectively to these three outcomes, the teachers label being accepted, the student's label being correct and and the student's label being incorrect.

Let us first look at verifying the label on a sample pattern from θ_1 at the n^{th} stage of learning. The "expected value" is given by,

$$\begin{aligned} E\{\text{value } |x\epsilon\theta_1\} &= 0 \left\{P_n \text{ (accepting teacher's label } |x\epsilon\theta_1)\right\} \\ &\quad + a' \left\{P_n \text{ (good label } |x\epsilon\theta_1)\right\} \\ &\quad - b'\left\{P_n \text{ (bad label } |x\epsilon\theta_1)\right\} \\ &= a' \int_T^{\infty} N\left((2\beta-1)\, f_{X|\theta_1}(x|\theta_1),\ \frac{f_{X|\theta_1}(x|\theta_1)}{\sqrt{n}\,(2\,\sqrt{\pi})^p}\right) d\xi \ . \\ &\quad - b'\int_{-\infty}^{-T} N\left((2\beta-1)\, f_{X|\theta_1}(x|\theta_1),\ \frac{f_{X|\theta_1}(x|\theta_1)}{\sqrt{n}\,(2\,\sqrt{\pi})^p}\right) d\xi. \end{aligned}$$

Doing the necessary algebra, it can be shown that the value of T that maximizes $E\{\text{value } |x\epsilon\theta_1\}$ is given by

$$\begin{aligned} T &= \frac{\ell_n(\frac{b'}{a'})}{2(2\,\sqrt{\pi})^p\,\sqrt{n}\,(2\beta-1)} \\ &= \frac{c_0}{\sqrt{n}\,(2\beta-1)} \ , \end{aligned} \qquad (20)$$

where

$$c_0 = \frac{\ell_n(\frac{b'}{a'})}{2(2\sqrt{\pi})^p} \ .$$

Proceeding along the same lines it can be shown that $E\{\text{value } |x\epsilon\theta_2\}$, is also maximum at T given in Equati (20). This implies that irrespective of whether $x\epsilon\theta_1$ or $x\epsilon\theta_2$, the "average value" of correction is maximum if T is chosen according to Equation (20).

The form of T given in Equation (20) is the same as the one given in Equation (19) for the minimax approach. The only difference is in the constants appearing in the expression. These constants are determined by the choice of the maximum acceptable value of the probability

of bad label in the first approach or the value function in the decision theory approach.

The algorithm for error correction now is:

Accept the label provided by the teacher for x if

$$\left| \hat{f}_{X|\hat{\theta}_1;n}(x|\hat{\theta}_1) - \hat{f}_{X|\hat{\theta}_2;n}(x|\hat{\theta}_2) \right| < T.$$

Correct the label to $\hat{\theta}_1$ if

$$\hat{f}_{X|\hat{\theta}_1;n}(x|\hat{\theta}_1) > \hat{f}_{X|\hat{\theta}_2;n}(x|\hat{\theta}_2) + T$$

and to $\hat{\theta}_2$ if

$$\hat{f}_{X|\hat{\theta}_2;n}(x|\hat{\theta}_2) > \hat{f}_{X|\hat{\theta}_1;n}(x|\hat{\theta}_1) + T \qquad (21)$$

where T is the threshold given in Equation (19) for the minimax approach and in Equation (20) for the decision theory approach.

Properties of Thresholded Error Correction:

Besides being an easy algorithm to implement, the proposed error correction scheme has the following desirable properties:

1) The maximum probability of error correction occurs on samples that come from close to the modes of the density functions.
2) At any given stage of learning, the probability that the student corrects an error made by the teacher, given that the teacher is in fact in error, increases as β increases, i.e. with a better teacher, there is a better chance that the student corrects an error.
3) The teacher is gradually phased out as the knowledge acquired by the student increases.

Let us concern ourselves with correcting a possible error on the label of a sample x that belongs to category θ_1. The probability of error correction on the label of x is given by

$$P_n(\text{error correction}|x\varepsilon\theta_1) = (1-\beta)\{P(\hat{f}_{X|\hat{\theta}_1;n}(x|\hat{\theta}_1)>\hat{f}_{X|\hat{\theta}_2;n}(x|\theta_2)+T|x\varepsilon\theta_1)\}$$

$$= (1-\beta)\int_T^{\infty} N\left((2\beta-1)f_{X|\theta_1}(x|\theta_1),\ \frac{f_{X|\theta_1}(x|\theta_1)}{\sqrt{n}\ (2\ \sqrt{\pi})^p}\right)d\xi .$$

From the above, it can be easily verified that if $f_{X|\theta_1}(x_1|\theta_1)>f_{X|\theta_1}(x_2|\theta_1)$, then P_n (error correction $|x_1\varepsilon\theta_1$) > P_n (error correction $|x_2\varepsilon\theta_1$). Hence, the maximum value of the probability of correcting the label on a sample $x\varepsilon\theta_1$ occurs if $f_{X|\theta_1}(x|\theta_1)$ is maximum. Similarly it can be shown that the maximum value of the probability of correcting the label on a sample $x\varepsilon\theta_2$ occurs if $f_{X|\theta_2}(x|\theta_2)$ is maximum. These two statements establish the first property listed above. Since samples are more likely to have come from near the modes, it is desirable to have a larger probability of correction here.

The probability that the student corrects a label error on a sample x from category θ_1, given that the teacher made an error, is

$$P_n\ (\text{error correction}\ |x\varepsilon\theta_1 \text{ and the teacher made an error}) =$$

$$\int_T^{\infty} N\left((2\beta-1)\ f_{X|\theta_1}(x|\theta_1),\ \frac{f_{X|\theta_1}(x|\theta_1)}{\sqrt{n}\ (2\ \sqrt{\pi})^p}\right)d\xi \quad .$$

$$= \int_{\frac{[T-(2\ -1)a]c}{\sqrt{a}}}^{\infty} N(0,1)d\xi \quad ,$$

where

$$a = f_{X|\theta_1}(x|\theta_1) \quad \text{and} \quad c = (2\ \sqrt{\pi})^{\frac{p}{2}}\ n^{\frac{1}{4}} \quad .$$

The lower limit of the integral decreases as β increases and hence the probability that the student corrects an error on the label of a sample pattern from category θ_1, given that the teacher made an error, increases as β increases. A similar argument may be given for x from category θ_2 and hence the property that with a better teacher, there is a better chance that the student corrects an error.

The probability that the student provides his own label for say, a sample pattern x from category θ_1 is

$$P_n(\text{student provides a label } | x\varepsilon\theta_1) =$$

$$1-P\left(\left|\hat{f}_{X|\hat{\theta}_1;n}(x|\hat{\theta}_1) - \hat{f}_{X|\hat{\theta}_2;n}(x|\hat{\theta}_2)\right| < T | x\varepsilon\theta_1\right)$$

$$= 1 - \int_{\left[\frac{-T-(2\beta-1)a}{\sqrt{a}}\right]c}^{\left[\frac{T-(2\beta-1)a}{\sqrt{a}}\right]c} N(0,1)d\xi$$

It can be seen that as T increases the value of the above integral increases and hence the probability that the student provides his own label decreases. Conversly as T decreases, the probability that the student provides his own label increases. Since T is a decreasing function of n, T will be large in the initial stages of learning and hence the probability that the student provides his own label is small. This means the student accepts whatever the teacher says when learning begins. As $n \to \infty$, $T \to 0$ and the probability that the student provides his own label $\to 1$, i.e. in the advanced stages of learning, the student provides his own label on each sample and learns independently without the aid

of the teacher. This gradual phasing out of teacher also occurs in most real life learning situations.

The proposed error correcting learning scheme checks the label on one sample at a time serially. Approximate estimators can also be updated serially in a polynomial form as suggested by Sprecht [9]. After updating, only the coefficients of the polynomial are retained and the samples are discarded. A question that is left open here is whether it would be better to store all the samples and verify the labels on all the (n-1) prior samples at the n^{th} stage of learning. The authors feel that the storage requirements and the computa . n involved for doing this will be formidable when the dimension of the patterns and the sample size are large, both of which are common in pattern recognition problems.

Even though the expressions for threshold given in Equations (19) and (20) display many . . rable properties no claim can be made about the "optimality" of these expressions. One of the shortcomings of the analysis presented in this lies in treating β as constant. Due the error correction, the effective value of β, defined as the ratio of the number of sample patterns with correct labels to the total number of sample patterns is changing. A formulation of this change is difficult, if at all possible. The probability statements about the outcomes of error correction involve the unknown density functions. Whereas for the teacher β is independent of x, the sample being labeled, the performance of the student will depend on the value of x and his past performance. If the error correction has been done badly at the initial stages of learning, then error correction on subsequent samples will also be bad. This fundamental difference in labeling procedure presents a very formidable step in the analysis of performance of the error correcting

scheme. The proposed error correction scheme was simulated on the computer and the results of the simulation are presented in the next section.

IV. SIMULATIONS

The performance of the proposed learning scheme was evaluated through simulations on the digital computer. The conditional density functions $f_{X|\theta_1}$ and $f_{X|\theta_2}$ used in the simulations are shown in Figure 2. Samples were drawn randomly from these two categories with $P(\theta_1) = P(\theta_2) = 1/2$ and the labeling was done according to (1). The learning scheme without error correction accepted the label provided by the teacher and the density functions $f_{X|\hat{\theta}_1}$ and $f_{X|\hat{\theta}_2}$ were estimated according to (8) and (9). A total of N_T samples were used for learning. Using the estimates of the density functions based on N_T samples, 40 test samples were classified according to (10).

The error correcting scheme learned from the same set of N_T samples, according to algorithm (11). The value of T corresponded to α, the maximum probability of bad label equal to 0.05 or values of a' and b' such that a'/b' = e. Based on the final estimate of the density functions, the same 40 test samples were classified.

For each value of β, ten runs were made. The risk for each run was taken to be the ratio of the number of test samples that were misclassified to the total number of test samples classified. The average risk for the learning scheme was taken to be the average of the risks on ten runs. Figure 3 shows a plot of the average risk versus β for the two learning schemes, for a sample size $N_T = 20$. Figure 4 shows the same plot for a sample size $N_T = 60$.

It appears from Figures 3 and 4 that error correction on the average improves the performance of the learning scheme. A rather interesting aspect of these plots is that error correction does not seem to improve the performance very much for either very high or very low values of β. At lower values of β, i.e. with a very bad teacher, the amount of correction is small because the student does not learn enough to question his teacher very often. At higher values of β, i.e. with a very good teacher, the student acquires his limiting knowledge quickly and error correction does not help here since error correction does not increase the limiting knowledge. Hence it appears that error correction is most effective when the teacher is mediocre.

Simulations were done for the unequal sample size case with $P(\theta_1) = 0.9$ and $P(\theta_2) = 0.1$. The simulation procedure is identical to the one described above except for the error correction algorithm. The algorithm used in this case is given in [10]. Figure 5 shows a plot of average risk versus β for this simulation. Once again it appears that error correction leads to an improvement in the performance of the learning scheme.

V. CONCLUSIONS

In this paper we have proposed a thresholded error correcting scheme for learning with an imperfect teacher. Expressions were derived for the value of the threshold as a function of the reliability of the teacher, the sample size and a subjective constant. The proposed scheme provides a simple means for combining the knowledge acquired by the student and the knowledge of the teacher. It is possible to control the extent to which the student depends on his teacher. Through computer simulations, we have shown that error correction leads to an improvement in the performance of the learning scheme.

We have presented only one of many possible error correcting schemes for learning with an imperfect teacher. Whether the scheme presented in this paper is the "best" is not known. However, the authors feel that this study will aid in an understanding of the problem of error correction in learning with an imperfect teacher and may suggest other optimum schemes of error correction.

More work on this scheme is needed, theoretically to study convergence and experimentally to apply this procedure to more than two categories of patterns.

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CAPTIONS FOR FIGURES

Figure 1. Model for the Error Correcting Procedure

Figure 2. Density Functions used in Simulations

Figure 3. Effect of Error Correction on Performance

Figure 4. "

Figure 5. "

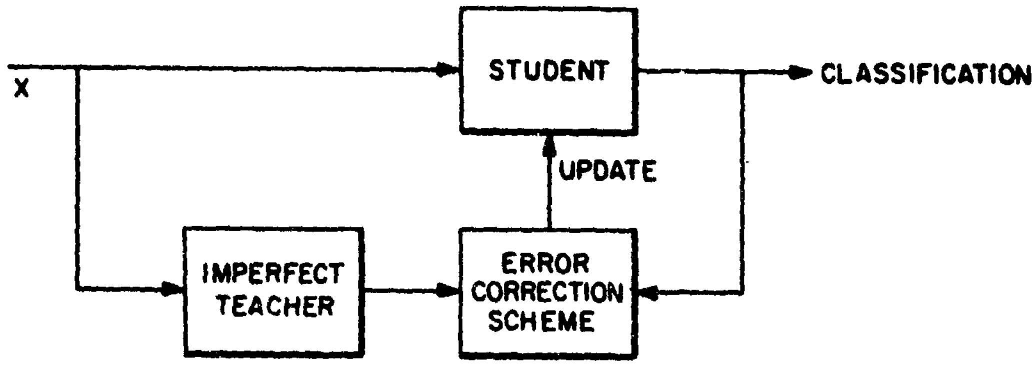

Figure 1. Model for the Error Correcting Procedure

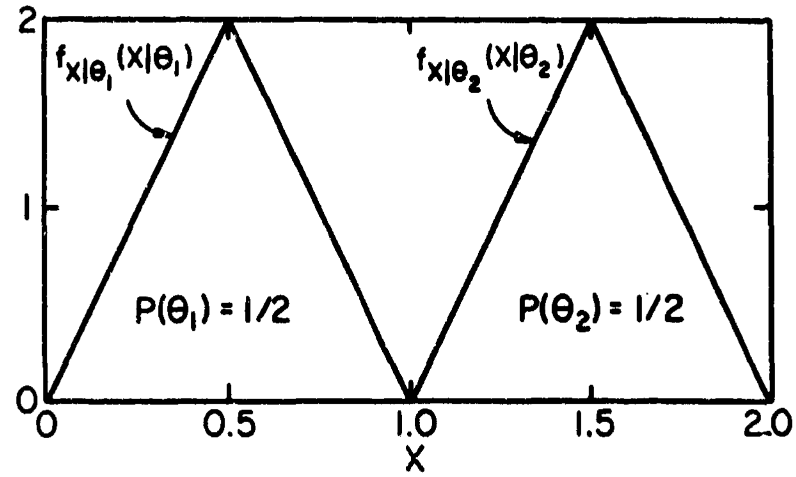

Figure 2. Non-overlapping Densities Used in Simulation

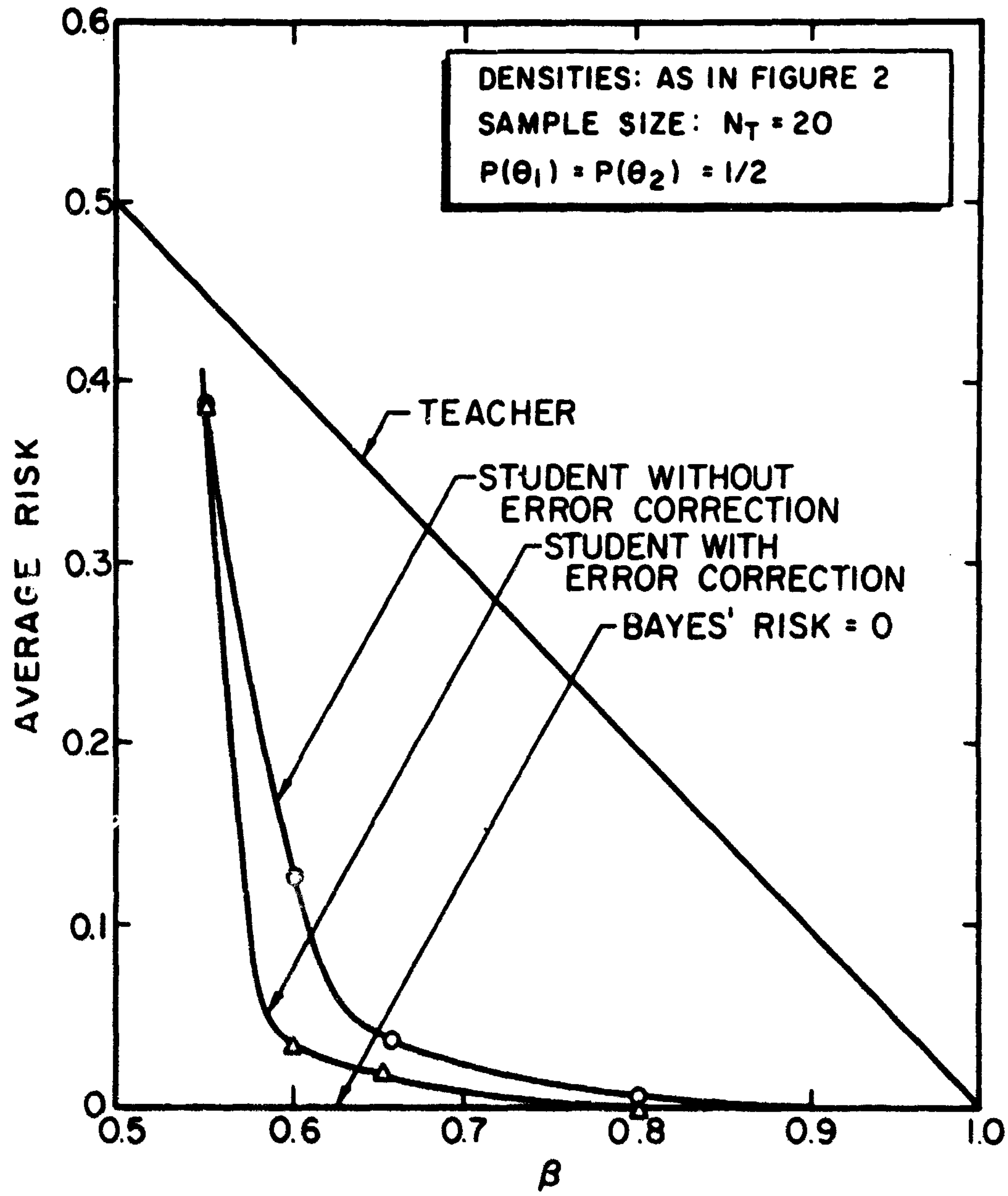

Figure 3. Effect of Error Correction on Performance

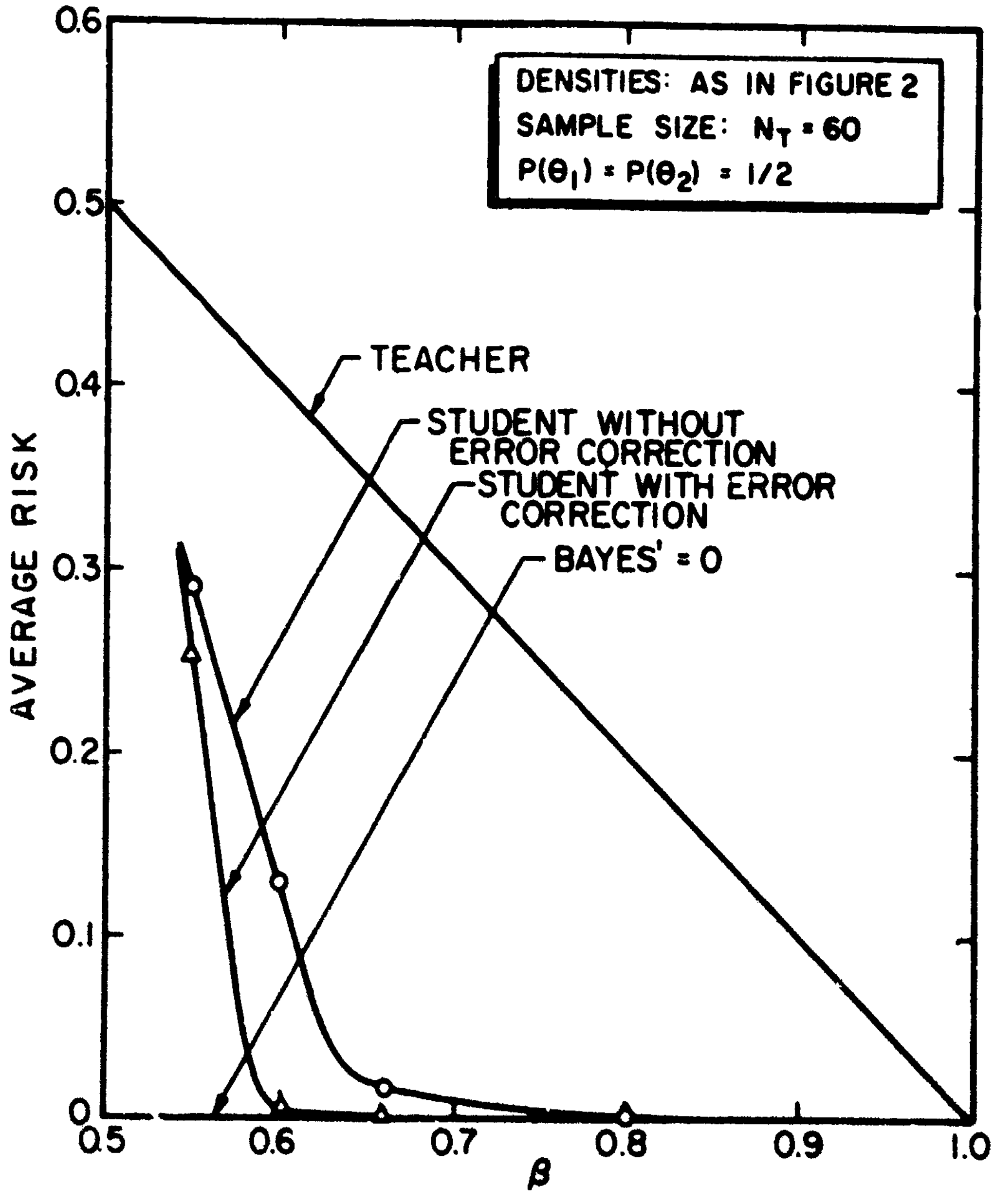

Figure 4. Effect of Error Correction on Performance

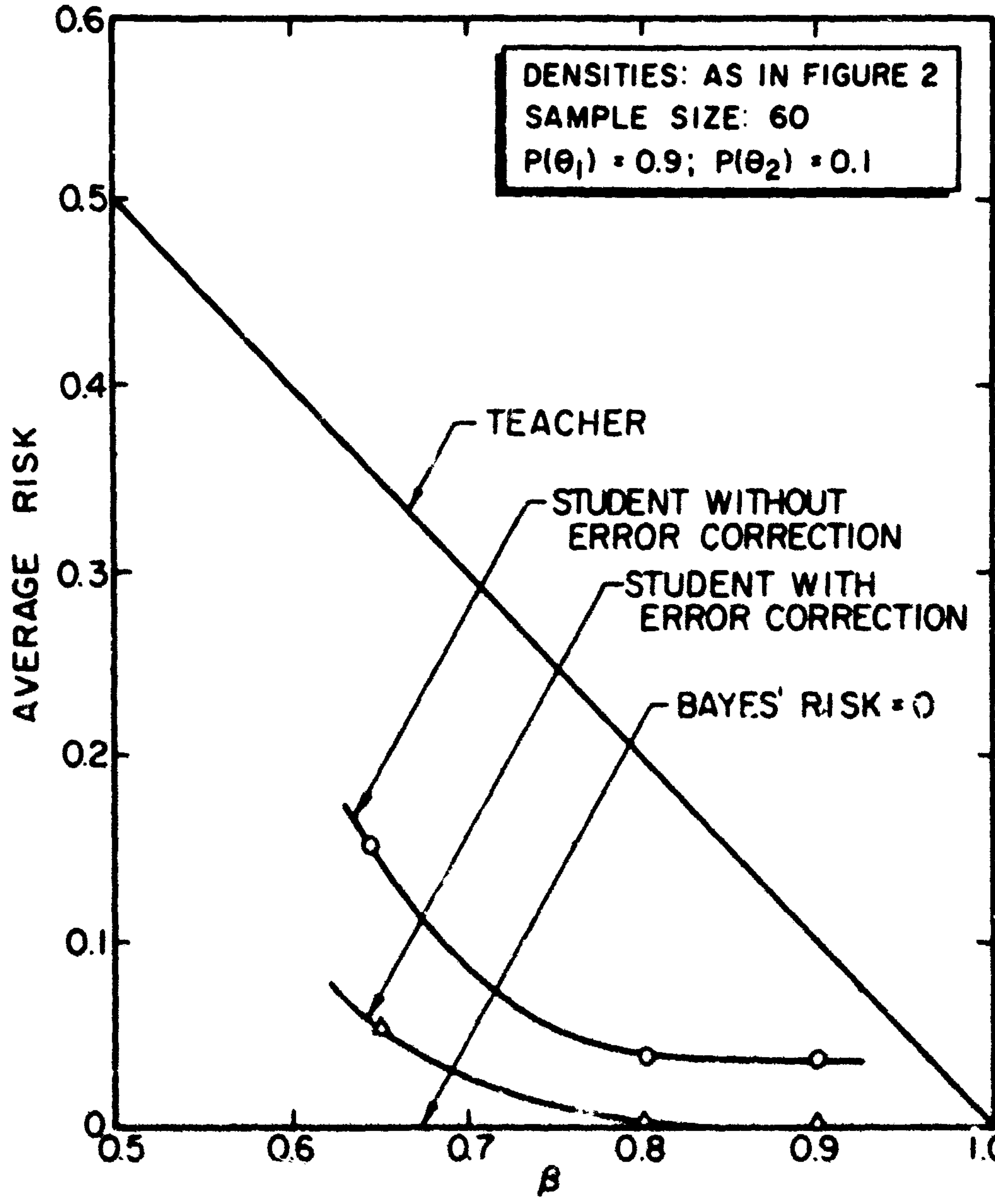

Figure 5. Effect of Error Correction on Performance

APPENDIX B

```
ASMB,A,B,L,T
      ORG 100B        PROGRAM STARTS AT 100 OCTAL.
BEGIN NOP
      LDA FL          LOAD TAPE COMMAND WORD. FILE MK.
      OTA 11B
START NOP
      HLT
      NOP             LOAD SW'S WITH NO. RECORDS.
      LIA 1
      CMA             COMPLEMENT REGISTER A.
      INA             ADD 1 TO A TO GET 2'S COMPL.
      STA REC         STORE 2'S COMPL IN REC.
ENTER NOP
      HLT
      NOP             PUSH RUN WHEN READY TO START PGM
      LDA REC
      STA CNT         INITIALIZE RECORD COUNT.
      CLC 0           TURN OFF ALL I/O.
      CLB             CLEAR REGISTER B-PARITY ERR CNT.
      CLF 0           TURN INTERRUPT OFF.
FIRST LDA CNTL1       INITIALIZE DMA1 TO READ ADC.
      OTA 6           CONTROL WORD ONE.
      CLC 2
      LDA ADR1
      OTA 2           CONTROL WORD 2.
      STC 2
      LDA NBUF        NBUF IS "WORDS PER RECORD".
      OTA 2           CONTROL WORD 3.
      STC 14B,C       START ADC.
      STC 6,C         START DMA1.
LOOP  LDA CNTL1       INITIALIZE DMA2 TO READ ADC.
      OTA 7            CW1
      CLC 3
      LDA ADR2
      OTA 3           CW2
      STC 3
      LDA NBUF
      OTA 3           CW3
      SFC 6           SKIP FLAG CLEAR-SKIP DMA1 BUSY.
      HLT 6           ERROR HALT.
      SFS 6           SKIP FLAG SET-SKIP WHEN DMA1 RDY
      JMP *-1         WAIT UNTIL DMA1 IS FINISHED.
      NOP
      STC 14B,C
      STC 7,C         START ADC & START DMA2.
THIRD LDA CNTL2       INITIALIZE DMA1 TO WRITE TAPE.
      OTA 6
      CLC 2
```

Figure B-1. ADC1 Program

```
      LDA ADR10
      OTA 2         CW2
      STC 2
      LDA NBUF
      OTA 2         CW3
      SFS 11B       SKIP FLAG SET-SKIP WHEN TAPE RDY
      JMP *-1       WAIT UNTIL TAPE IS READY.
      LDA OUT       GET TAPE COMMAND WORD FOR OUTPT
      OTA 11B,C     OUTPUT COMMAND WORD TO TAPE.
      STC 6,C       START DMA1 TO TAPE.
      SFS 6         SKIP FLAG SET-SKIP IF DMA1 FIN.
      JMP *-1       WAIT UNTIL DMA1 IS FINISHED.
      LIA 11B       GET TAPE STATUS WORD.
      AND MASK1     CHECK PARITY STATE.
      SZA           SKIP IF PARITY IS OK.
      JSB ERROR     GO TO ERROR ROUTINE-BAD PARITY.
      ISZ CNT       INCREMENT RECORD COUNT.
      JMP *+12
      LDA JOB1      HALT ON RECORDS COMPLETE WITH
      HLT 6         (A) REGISTER = 70707*******
      JSB ENDFL     PUSH START TO GET EOF MARK*****
      NOP
      JSB REWND     TAPE REWIND ROUTINE.
      CLC 0         TURN OFF ALL I/O UNITS.
      LDA JOB2      HALT ON NORMAL JOB COMPLETE----
      HLT 6         LOAD A NEW REEL OF TAPE AND PUSH
      NOP           RUN TO REPEAT ENTIRE PROGRAM.
      JMP BEGIN     ******************************
      NOP           ******************************
FOUR  LDA CNTL1     INITIALIZE DMA1 TO READ ADC.
      OTA 6
      CLC 2
      LDA ADR1
      OTA 2         CW2
      STC 2
      LDA NBUF
      OTA 2         CW3
      SFC 7         SKIP IF DMA2 IS BUSY.
      HLT 7         ERROR HALT.
      SFS 7         SKIP IF BUFFER2 IS FULL.
      JMP *-1       WAIT UNTIL DMA2 FLAG IS SET.
      STC 14B,C     START ADC.
      STC 6,C       START DMA1.
      LDA CNTL2     INITIALIZE DMA2 TO WRITE TAPE.
      OTA 7         CW1
      CLC 3
      LDA ADR20
      OTA 3         CW2
```

Figure B-1. ADC1 Program (continued)

```
      STC 3
      LDA NBUF
      OTA 3         CW3
      SFS 11B       SKIP WHEN TAPE IS READY.
      JMP *-1       WAIT UNTIL TAPE IS READY.
      LDA OUT       GET TAPE COMMAND WORD.
      OTA 11B,C     START TAPE MACHINE.
      STC 7,C       START DMA2 TO TAPE.
      SFS 7         SKIP WHEN DMA2 IS FINISHED.
      JMP *-1       WAIT UNTIL DMA2 IS FINISHED.
      LIA 11B       GET TAPE STATUS WORD.
      AND MASK1     CHECK PARITY STATE.
      SZA           SKIP IF PARITY IS OK.
      JSB ERROR     BAD PARITY.
      ISZ CNT       INCREMENT RECORD COUNT.
      JMP *+13
      LDA JOB1
      HLT 7         RECORDS COMPLETE. PUSH RUN TO
      NOP           WRITE EOF AND REWIND TAPE.
      JSB ENDFL     GO TO END-OF-FILE ROUTINE.
      JSB REWND     GO TO REWIND ROUTINE.
      NOP
      CLC 0         TURN OFF ALL I/O UNITS.
      LDA JOB2
      HLT 7         PUSH REN TO REPEAT ENTIRE PGM.
      NOP           LOAD NEW TAPE****************
      NOP           *****************************
FIVE  JMP BEGIN     *****************************
      JMP LOOP      GO READ ANOTHER RECORD.
ERROR NOP           PARITY ERROR ROUTINE.
      INB           INCREMENT B REGISER.
      JMP ERROR,I   RETURN TO MAIN PROGRAM.
REWND NOP           REWIND ROUTINE.
      SFS 11B       SKIP WHEN TAPE IS READY.
      JMP *-1       WAIT UNTIL TAPE IS READY.
      LDA REW       GET REWIND COMMAND WORD.
      OTA 11B,C     REWIND TAPE.
      SFS 11B       SKIP WHEN TAPE IS REWOUND.
      JMP *-1
      JMP REWND,I   RETURN TO MAIN PROGRAM.
ENDFL NOP           END-OF-FILE ROUTINE.
      SFS 11B       SKIP WHEN TAPE IS READY.
      JMP *-1
      LDA FILE      GET TAPE EOF COMMAND WORD.
      OTA 11B,C     WRITE E-O-F.
      SFS 11B
```

Figure B-1. ADC1 Program (continued)

```
      JMP *-1       WAIT UNTIL TAPE IS READY.
      JMP ENDFL,I   RETURN TO MAIN PROGRAM.
FILE  OCT 35        E-O-F COMMAND WORD.
CNTL1 OCT 120014    CONTROL WORD NO. 1 FOR DMA.
NBUF  DEC -2000     NUMBER OF WORDS PER RECORD.
OUT   OCT 31        TAPE WRITE COMMAND WORD.
CNTL2 OCT 160010    CONTROL WORD NO. 2 FOR DMA.
ADR1  OCT 102000    BUFFER1 STARTING ADDRESS. 2000B
ADR2  OCT 106000    BUFFER2 STARTING ADDRESS. 6000B
ADR10 OCT 002000    BUFFER1 STARTING ADDRESS. 2000B
ADR20 OCT 006000    BUFFER2 STARTING ADDRESS. 6000B
MASK1 OCT 2         MASK TO CHECK PARITY ON TAPE.
REW   OCT 201       TAPE REWIND COMMAND WORD.
REC   NOP           ENTER NUMBER OF RECORDS HERE.
CNT   NOP           PUT 2'S COMPLEMENT OF RECORDS H
FL    OCT 35        TAPE E-O-F COMMAND WORD.
JOB1  OCT 77777
JOB2  OCT 70707
      END
 END OF TAPE
 END OF TAPE
```

Figure B-1. ADC1 Program (continued)

```
ASMB,A,B,L,T
      ORG 100B
BEGIN NOP
      LDA FL
      OTA 11B
HLT1  HLT
      LIA 1
      CPA ZERO
      JMP START
      CMA
      INA
      STA CNT
LOOP1 LDA SPC1
      OTA 11B
      ISZ CNT
      JMP LOOP1
START NOP
HALT2 HLT
      CLC 0
      CLB
      CLF 0
      LDA CNTL1
      OTA 6
      CLC 2
      LDA ADR1
      OTA 2
      STC 2
      LDA NBUF
      OTA 2
      STC 14B,C
      STC 6,C
      SFS 6
      JMP *-1
      LDA CNTL2
      OTA 6
      CLC 2
      LDA ADR10
      OTA 2
      STC 2
      LDA NBUF
      OTA 2
      SFS 11B
      JMP *-1
      LDA OUT
      OTA 11B,C
      STC 6,C
      SFS 6
      JMP *-1
      LIA 1
      AND MASK1
```

Figure B-2. ADC2 Program

```
        SZA
        JMP ERROR
        LDA ZERO
        JMP *+1
ERROR   LDA ONE
HALT3   HLT
        LIA 1
        CPA ZERO
        JMP START
        CPA BACK
        JMP BACK1
        CPA ENDX
        JMP REW
BACK1   LDA SPC2
        OTA 11B
        SFS 11B
        JMP *-1
        JMP START
REW     NOP
        SFS 11B
        JMP *-1
        LDA REW1
        OTA 11B,C
        SFS 11B
        JMP *-1
        CLC 0
        HLT
ZERO    OCT 0
ONE     OCT 1
BACK    OCT 1
ENDX    OCT 2
CNTL1   OCT 120014
ADR1    OCT 102000
NBUF    DEC -2048
CNTL2   OCT 160010
ADR10   OCT 002000
SPC1    OCT 3
OUT     OCT 31
SPC2    OCT 41
FL      OCT 35
MASK1   OCT 2
REW1    OCT 201
CNT     NOP
        END
 END OF TAPE
```

Figure B-2   ADC2 Program (continued)

```
                     ASMB,B,L,A,C,T
      00100               ORG 100B       PROGRAM STARTS AT 100 OCTAL.
*
*****DATACON-CONVT PROGRAM
*
*    DATA READ FROM A/D CONVERTOR IS PUT ON MAGNETIC TAPE
*    IN A FORMAT COMPATABLE TO FORTRAN 360.  USE A SYSTEM
*    360 STANDARD LABELED TAPE.
*
*****
*
*    FIRST OPERATION IS TO CHECK FOR LEGAL LABELED TAPE.
*
      00100 060462        LDA  HDCON     LOAD FIRST CONTROL WORD.
      00101 102606        OTA 6          TYPE OF OPERATION AND UNIT USE
      00102 106702        CLC 2          PREPARE FOR SECOND CONTROL WOR
      00103 060461        LDA HDAD       SECOND CONTROL WORD.
      00104 102602        OTA 2          INPUT ADDRESS IN CORE FOR FIRS
      00105 102702        STC 2          PREPARE--
      00106 060460        LDA HDLEN      LENGTH OF DATA FIELD TO BE REA
      00107 102602        OTA 2
      00110 060463        LDA READ       LOAD READ COMMAND FOR MAG. TAP
      00111 103611        OTA 11B,C      START TAPE DECK.
      00112 103706        STC 6,C        START THE DMA CHANNEL # 2.
      00113 102311        SFS 11B        WAIT FOR TAPE DECK.
      00114 024113        JMP *-1
      00115 060464        LDA VO         LOAD "VO" FROM 360 HEADER VOL1
      00116 020703        XOR 703B       CHECK FIRST DATA WORD.
      00117 002002        SZA
      00120 024370        JMP DEAD       FIRST WORD DID NOT COPARE--FOR
      00121 060465        LDA L1         LOAD "L1" FROM 360 HEADER RECO
      00122 020701        XOR 701B
      00123 002002        SZA            CHECK SECOND DATA WORD.
      00124 024370        JMP DEAD
      00125 014373        JSB FWDSP      SKIP SECOND FILE
      00126 014373        JSB FWDSP      SKIP THIRD FILE.
      00127 014373        JSB FWDSP      CHECK FOURTH FILE FOR TAPE MAR
      00130 034000        ISZ 0
      00131 024370        JMP DEAD       TAPE MARK NOT HERE AS SHOULD B
*
***** OPERATOR     ION--FORWARD SPACE SPECIFIED NUMBER OF RECORDS.
*
*     SET BIT "15"
*****
*
      00132 102501        LIA 1       LOAD SWITCH REGISTURE
      00133 002020        SSA         CHECK SWITCH SETTING
      00134 014421        JSB FWDNO     JUMP TO SUBROUTINE TO FORWARD SP
*
*****
*
      00135 102000  START HLT 0      LOAD SW. REG. WITH NO. RECORDS.
      00136 102501        LIA 1
      00137 003004        CMA,INA       GENERATE TWOS COMPLEMENT
      00140 070466        STA REC      STORE 2'S COMPL IN REC.
      00141 102001  ENTER HLT 1     PUSH RUN TO START PROGRAM
      00142 060466        LDA REC
```

Figure B-3. ADC2A Program

```
00143 070467       STA CNT      INITIALIZE RECORD COUNT.
00144 106700       CLC 0        TURN OFF ALL I/O.
00145 002400       CLA          CLEAR A FOR ERROR COUNT
00146 070455       STA NER      SET ERROR COUNTER
00147 103100       CLF 0        TURN INTERRUPT OFF.
00150 060442 FIRST LDA CNTL1    INITIALIZE DMA1 TO READ ADC.
00151 102606       OTA 6        CONTROL WORD ONE.
00152 106702       CLC 2
00153 060451       LDA ADR1
00154 102602       OTA 2        CONTROL WORD 2.
00155 102702       STC 2
00156 060443       LDA NBUF     NBUF IS "WORDS PER RECORD".
00157 102602       OTA 2        CONTROL WORD 3.
00160 103714       STC 14B,C    START ADC.
00161 103706       STC 6,C      START DMA1.
00162 060442 LOOP  LDA CNTL1    INITIALIZE DMA2 TO READ ADC.
00163 102607       OTA 7         CW1
00164 106703       CLC 3
00165 060452       LDA ADR2
00166 102603       OTA 3        CW2
00167 102703       STC 3
00170 060443       LDA NBUF
00171 102603       OTA 3        CW3
00172 102206       SFC 6        SKIP FLAG CLEAR-SKIP DMA1 BUSY.
00173 102006       HLT 6        ERROR HALT.
00174 102306       SFS 6        SKIP FLAG SET-SKIP WHEN DMA1 RDY
00175 024174       JMP *-1        WAIT FOR DMA1.
00176 103714       STC 14B,C
00177 103707       STC 7,C      START ADC & START DMA2.
00200 060450 THIRD LDA CNTL2    INITIALIZE DMA1 TO WRITE TAPE.
00201 102606       OTA 6
00202 106702       CLC 2
00203 060444       LDA RADR1
00204 102602       OTA 2        CW2
00205 102702       STC 2
00206 060446       LDA NBUFF
00207 102602'      OTA 2        CW3
00210 060443       LDA NBUF     LOAD COMPLEMENT OF NUMBER OF RECOR
00211 070416       STA COUNT    SAVE COUNTER
00212 064453       LDB ADR10    STARTING ADDRESS OF A-D BUFFER
00213 074417       STB NUM
00214 044443       ADB NBUF     BACK UP FOR OUTPUT POINTER
00215 060447       LDA OUT      LOAD MAG TAPE "WRITE" COMMAND
00216 000040       CLE
00217 102311       SFS 11B       SKIP FLAG SET-SKIP WHEN TAPE RDY
00220 024217       JMP *-1       WAIT UNTIL TAPE IS READY.
00221 103611       OTA 11B,C     OUTPUT COMMAND WORD TO TAPE.
00222 103706       STC 6,C       START DMA1 TO TAPE.
00223 014345       JSB CONVT     START CONVERTING NUMBERS
00224 102306       SFS 6         SKIP FLAG SET-SKIP IF DMA1 FIN.
00225 024224       JMP *-1       WAIT UNTIL DMA1 IS FINISHED.
00226 102511       LIA 11B       GET TAPE STATUS WORD.
00227 010456       AND MASK1     CHECK PARITY STATE.
00230 002002       SZA           SKIP IF PARITY IS OK.
00231 014317       JSB ERROR     GO TO ERROR ROUTINE-BAD PARITY.
00232 034467       ISZ CNT       INCREMENT RECORD COUNT.
00233 024244       JMP FOUR
```

Figure B-3. ADC2A Program (continued)

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```
00234 060472  FIVE  LDA JOB1    HALT ON RECORDS COMPLETE WITH
00235 064455        LDB NER      LOAD NUMBER OF ERRORS
00236 106700        CLC 0       TURN OFF ALL I/O DEVICES.
00237 102066        HLT 66B     HLT--END OF RUN..........
00240 014330        JSB ENDFL    PUSH START TO GET EOF MARK*****
00241 014407        JSB VOLEN      SUBROUTINE TO END VOLUME.
00242 014322        JSB REWND    TAPE REWIND ROUTINE.
00243 024371        JMP DEAD+1
00244 060442  FOUR  LDA CNTL1    INITIALIZE DMA1 TO READ ADC.
00245 102606        OTA 6
00246 106702        CLC 2
00247 060451        LDA ADR1
00250 102602        OTA 2        CW2
00251 102702        STC 2
00252 060443        LDA NBUF
00253 102602        OTA 2        CW3
00254 102207        SFC 7        SKIP IF DMA2 IS BUSY.
00255 102007        HLT 7        ERROR HALT.
00256 102307        SFS 7        SKIP IF BUFFER2 IS FULL.
00257 024256        JMP *-1      WAIT UNTIL DMA2 FLAG IS SET.
00260 103714        STC 14B,C
00261 103706        STC 6,C      START DMA1.
00262 060450        LDA CNTL2    INITIALIZE DMA2 TO WRITE TAPE.
00263 102607        OTA 7        CW1
00264 106703        CLC 3
00265 060445        LDA RADR2
00266 102603        OTA 3        CW2
00267 102703        STC 3
00270 060446        LDA NBUFF
00271 102603        OTA 3        CW3
00272 060443        LDA NBUF     LOAD COMPLEMENT OF NUMBER OF RECO
00273 070416        STA COUNT    SAVE IN COUNTER
00274 064454        LDB ADR23    STARTING ADDRESS OF A-D BUFFER
00275 074417        STB NUM      STORE ADDRESS--INPUT POINTER
00276 044443        ADB NBUF     BACK UP THE OUTPUT POINTER
00277 060447        LDA OUT      LOAD MAG TAPE "WRITE" COMMAND
00300 000040        CLE
00301 102311        SFS 11B      SKIP WHEN TAPE IS READY.
00302 024301        JMP *-1      WAIT UNTIL TAPE IS READY.
00303 103611        OTA 11B,C    START TAPE MACHINE.
00304 103707        STC 7,C      START DMA2 TO TAPE.
00305 014345        JSB CONVT    START CONVERTING NUMBERS
00306 102307        SFS 7        SKIP WHEN DMA2 IS FINISHED.
00307 024306        JMP *-1      WAIT UNTIL DMA2 IS FINISHED.
00310 102511        LIA 11B      GET TAPE STATUS WORD.
00311 010456        AND MASK1    CHECK PARITY STATE.
00312 002002        SZA          SKIP IF PARITY IS OK.
00313 014317        JSB ERROR    BAD PARITY.
00314 034467        ISZ CNT      INCREMENT RECORD COUNT.
00315 024162        JMP LOOP
00316 024234        JMP FIVE
00317 000000  ERROR NOP          PARITY ERROR ROUTINE.
00320 034455        ISZ NER      UPDATE THE ERROR COUNT
00321 124317        JMP ERROR,I  RETURN TO MAIN PROGRAM.
00322 000000  REWND NOP          REWIND ROUTINE.
00323 102311        SFS 11B      SKIP WHEN TAPE IS READY.
00324 024323        JMP *-1      WAIT UNTIL TAPE IS READY.
```

Figure B-3. ADC2A Program (continued)

```
00325 061457          LDA REW       GET REWIND COMMAND WORD.
00326 103611          OTA 11B,C     REWIND TAPE.
00327 124322          JMP REWND,I   RETURN TO MAIN PROGRAM.
00330 000000   ENDFL  NOP           SUBROUTINE RETURN ADDRESS.
*
***** TO RETURN TO START--SET BIT "0"
*
00331 102501          LIA 1         LOAD SWITCH REGISTURE
00332 000010          SLA           CHECK LEAST SIGNIFICANT BIT
00333 024135          JMP START     JMP TO LOAD DATA
*
***** SET BIT "15" TO BACKSPACE A SPECIFIED NUMBER OF RECORDS.
*
00334 002020          SSA           CHECK BIT "15".
00335 024432          JMP BACK      JUMP TO SUB. TO BACK SPACE RECORD
*
*****
*
00336 102311          SFS 11B       SKIP WHEN TAPE IS READY.
00337 024336          JMP *-1
00340 060420          LDA FILE      GET TAPE EOF COMMAND WORD.
00341 103611          OTA 11B,C     WRITE E-O-F.
00342 102311          SFS 11B
00343 024342          JMP *-1       WAIT UNTIL TAPE IS READY.
00344 124330          JMP ENDFL,I   RETURN TO MAIN PROGRAM.
*
***** CONVERTING SUBROUTINE *****
*
*     A/D INPUT NUMBERS ARE CHANGED TO FORTRAN FLOATING WORDS.
*
00345 000000   CONVT  NOP           SPACE FOR SUBROUTINE RETURN ADDRE
00346 160417   STTT   LDA NUM,I      LOAD NUMBER TO BE CONVERTED
00347 010470          AND MSKK      DROP LEAST SIGNFICANT FIGURES(TWO
00350 001623          ELA,RAR       SAVE SIGN IN E REGISTURE
00351 002204          CME,INA       CORRECT SIGN-SET EXPONENT SIGN
00352 001325          RAR,ERA       MOVE IN BOTH SIGN BITS
00353 170001          STA 1,I       STORE IN ADDRESS GIVEN IN B REGIS
00354 006004          INB           UPDATE THE OUTPUT ADDRESS
00355 160417          LDA NUM,I     LOAD NUMBER AGAIN
00356 010471          AND MSKL      DROP ALL BUT LEAST TWO SIGNFICANT
00357 001323          RAR,RAR       ROTATE AROUND TO THE HIGH ORDER E
00360 170001          STA 1,I
00361 006104          CLE,INB       UPDATE THE OUTPUT ADDRESS
00362 034417          ISZ NUM       UPDATE THE INPUT ADDRESS
00363 034416          ISZ COUNT     UPDATE THE COUNTER,SKIP IF END
00364 024346          JMP STTT
00365 102211          SFC 11B        CHECK TO BE SURE TAPE DIDN'T GET
00366 102052          HLT 52B        TAPE DECK AHEAD OF CONVERSION...
00367 124345          JMP CONVT,I    SUBROUTINE RETURN.....
*
*    DEAD SUBROUTINEHEADER LABEL NOT ACCEPTABLE.
*
00370 014322   DEAD   JSB REWND        REWIND AN STANDBY.
00371 102025          HLT 25B          STOP FOR OPERATOR ACTION
00372 024100          JMP 100B         RETURN TO START OF PROGRAM
*     THE OPERATOR IS EXPECTED TO SUPPLY A NEW REEL OF TAPE--
*     A LABELED ONE BEFORE PUSHING "RUN".
```

Figure B-3. ADC2A Program (continued)

```
*
****************
*
*     SUBROUTINE TO FORWARD SPACE RECORD ON MAG TAPE UNIT
*
  00373 000000  FWDSP NOP          RETURN ADDRESS OR SUBROUTINE EXIT
  00374 060405        LDA FWD      LOAD FORWARD SPACE RECORD COMMAND
  00375 103611        OTA 11B,C    OUTPUT COMMAND
  00376 102311        SFS 11B    SKIP WHEN TAPE UNIT COMPLETED.
  00377 024376        JMP *-1      WAIT FOR COMPLETION OF OPERATION
  00400 102511        LIA 11B      LOAD STATUS WORD
  00401 010406        AND CWORD
  00402 002002        SZA          CHECK FOR TAPE MARK
  00403 003400        CCA          SET "A" TO -1 IF TAPE MARK SENSED
  00404 124373        JMP FWDSP,I  RETURN TO MAIN PROGRAM.
  00405 000003  FWD   OCT 3        TAPE COMMAND--FORWARD SPACE RECOR
  00406 000200  CWORD OCT 200      MASK FOR SENSING WHEN TAPE MARK P
*
*       UPON RETURN--  "A" IS 0 IF NO TPE MARK SENSED.
*                      "A" IS -1 IS TAPE MARK DETECTED
*
*
*
*      SUBROUTINE     ALLOWS OPTION OF ENDING VOLUME OR
*
*
  00407 000000  VOLEN NOP          SAVE RETURN ADDRESS AREA
  00410 102070        HLT 70B      HALT FOR OPERATOR RESPONSE
  00411 102501        LIA 1         LOAD SWITCH REGISTURE.
  00412 002020        SSA          CHECK OPERATORS INSTRUCTION
  00413 024135        JMP START    PREPARE TO LOAD DATA SET--MULTIPLE
  00414 014330        JSB ENDFL    PLACE SECOND FILE MARK--VOLUME END
  00415 124407        JMP VOLEN,I RETURN TO MAIN PROGRAM.
  00416 000000  COUNT OCT 0         COUNTER IN CONVERT ROUTINE
  00417 000000  NUM   OCT 0         INPUT POINTER IN CONVERT ROUTINE
  00420 000035  FILE  OCT 35        E-O-F COMMAND WORD.
***** FORWARD SPACE A SPECIFIED NUMBER OF RECORDS.
*
*
  00421 000000  FWDNO NOP           SUBROUTINE RETURN ADDRESS.
  00422 102014        HLT 14B
  00423 102501        LIA 1         LOAD NUMBER OF RECORDS TO FORWARD
  00424 003004        CMA,INA       GENERATE TWO'S COMPLEMENT.
  00425 070416        STA COUNT     STORE COUNTER.
  00426 014373        JSB FWDSP     GO TO SUB TO FORWARD SPACE ONE RE
  00427 034416        ISZ COUNT     CHECK COUNTER.
  00430 024426        JMP *-2       KEEP IN LOOP UNTIL SATISFIED.
  00431 124421        JMP FWDNO,I      SUBROUTINE RETURN
*
*****  BACKSPACE SUB.
*
  00432 060441  BACK  LDA BREC      LOAD COMMAND FOR BACK SPACING REC
  00433 070405        STA FWD       LOAD COMMAND IN FWDSP SUBROUTINE.
  00434 014421        JSB FWDNO     GO TO SUB. TO GET NO. OF RECORDS
  00435 060440        LDA FREC      LOAD FORWARD SPACE COMMAND
  00436 070405        STA FWD       RESTORE SUBROUTINE COMMAND WORD.
  00437 024135        JMP START     PREPARE TO LOAD DATA.
```

Figure B-3. ADC2A Program (continued)

```
00440 000003  FREC   OCT 3          FORWARD SPACE COMMAND.
00441 000041  BREC   OCT 41         BACK SPACE COMMAND.
00442 130014  CNTL1   OCT 130014     CONTROL WORD--NO "CLC" AT END OF
00443 174150  NBUF    DEC -1944     BUFFER LENGTH.
00444 000500  BADR1  OCT 500            TAPE OUTPUT BUFFER #1.
00445 010000  BADR2  OCT 10000          TAPE OUTPUT BUFFER #2.
00446 170314  NBUFF  DEC -3892
00447 000031  OUT    OCT 31         TAPE WRITE COMMAND WORD.
00450 160010  CNTL2  OCT 160010     CONTROL WORD NO. 2 FOR DMA.
00451 104334  ADR1   OCT 104334
00452 114034  ADR2   OCT 114034
00453 004334  ADR11  OCT 4334
00454 014134  ADR22  OCT 14134
00455 000000  NER    OCT 0          STORAGE FOR NUMBER OF PARITY ERRO
00456 000002  MASK1  OCT 2          MASK TO CHECK PARITY ON TAPE.
00457 000101  SBY    OCT 101       TAPE COMMAND--REWIND AND STAND BY
00460 177660  HDLEN  OCT -120      HEADER LENGTH
00461 117700  HDAD  OCT 117700    LOAD DATA TO CORE 7000B UP.
00462 160010  HDCON  OCT 160010    DMA CONTROL--USE UNIT 10
00463 000023  READ   OCT 23        MAG TAPE COMMAND TO READ.
00464 162726  VO     OCT 162726
00465 151761  LI     OCT 151761
00466 000000  REC    NOP            ENTER NUMBER OF RECORDS HERE.
00467 000000  CNT    NOP            PUT 2'S COMPLEMENT OF RECORDS H
00470 177774  MSKK   OCT 177774     MASK TO DROP LEAST TWO SIGNIFICAN
00471 000003  MSKL   OCT 3          MASK TO DROP ALL BUT LEAST TWO SI
00472 077777  JOB1   OCT 77777      LOADED INTO "A" WHEN RECORDS HAVE
*
* SET UP INITIAL CONSTANTS FOR FORTRAN TAPE FORMAT
 00500                ORG 500B
 00500 017150         DEC 7784
 00501 000000         OCT 0
 00502 017144         DEC 7780
 00503 000000         OCT 0
*
 10200                ORG 10200B      START TO SET UP CONSTANTS.
 10200 017150         DEC 7784     BYTE LENGTH OF BLOCK
 10201 000000         OCT 0            CONTROL WORD
 10202 017144         DEC 7780     BYTE LENGTH OF LRECL
 10203 000000         OCT 0            CONTROL WORD.
*
*
*          THIS IS NECESSARY SINCE FORTRAN WILL NOT ACCEPT
*              CORE TYPE DUMPS.  BLKSIZE AND LRECL MUST BE FURNISHED.
*
*  HALT 6 AND 7 (OCTAL) MEAN USER LOADED INPUT DATA FASTER
*     THAN TAPE IS LOADING DATA--SLOW INPUT RATE. 13000 WORDS
*     PER SECOND IS MAXIMUM RATE.
*
*            HALT 66---DATA LOADED PROPERLY--USER CHECK
*               "B" REGISTURE TO SEE IF ANY TAPE ERRORS
*               WERE DETECTED DURING LOADING.
*
                      END 7?B
** NO ERRORS*
```

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Figure B-3. ADC2A Program (continued)

```
                        ASMB,A,B,L,T
      16100                   ORG 16100B
      16100 000000  TITLE NOP              A PROGRAM TO READ A TAPE RECORD
      16101 000000        NOP              INTO CORE MEMORY.
      16102 000000  BEGIN NOP
      16103 106700        CLC 0            CLEAR ALL CONTROL BITS. I/O OFF.
      16104 103100        CLF 0            TURN OFF INTERRUPT SYSTEM.
      16105 006400        CLB              CLEAR B REGISTER.
      16106 062210        LDA CW1          FORWARD SPACE PAST FILE MARK.
      16107 102611        OTA 11B
      16110 062211        LDA CW2          BACKSPACE TO FIRST RECORD.
      16111 102611        OTA 11B
      16112 062220        LDA ONE          (A) = 177777 OCTAL.
      16113 102006  HALT1 HLT 6            HALT NO. 1
      16114 102501        LIA 1            LOAD SWITCHES WITH NUMBER OF
      16115 000000        NOP              RECORDS TO BE SKIPPED, OR WITH
      16116 000000        NOP              THE REWIND CODE(SW15 UP).
      16117 000000        NOP              PUSH "RUN" WHEN READY.
      16120 002020        SSA              SKIP IF SW15 IS DOWN.
      16121 026174        JMP REWND        GO TO REWIND(SW15 UP).
      16122 000000  SPACE NOP
      16123 003000        CMA              GET 2'S COMPLEMENT OF (A).
      16124 002004        INA
      16125 072207        STA COUNT        STORE (A) IN "COUNT".
      16126 000000        NOP
      16127 062210        LDA CW1          SPACE FORWARD CONTROL WORD.
      16130 102611        OTA 11B
      16131 102311        SFS 11B
      16132 026131        JMP *-1          WAIT UNTIL TAPE IS READY.
      16133 036207        ISZ COUNT        INCR COUNT-SKIP IF ZERO.
      16134 026130        JMP *-4          GO BACK AND SPACE AGAIN.
      16135 062221        LDA TWO          (A) = 000007 OCTAL.
      16136 000000  HALT2 NOP
      16137 102006        HLT 6            HALT NO. 2 PUSH "RUN" TO GO.
      16140 062212        LDA DMA1         INITIALIZE DMA1 TO READ TAPE.
      16141 102606        OTA 6
      16142 106702        CLC 2
      16143 062213        LDA ADDRS        CORE ADDRESS.
      16144 102602        OTA 2
      16145 102702        STC 2
      16146 062214        LDA WORDS        WORDS PER RECORD.
      16147 102602        OTA 2
      16150 102311        SFS 11B
      16151 026150        JMP *-1          WAIT UNTIL TAPE IS READY.
      16152 062215        LDA TAPE         TAPE COMMAND WORD.
      16153 103611        OTA 11B,C        READY THE TAPE.
      16154 103706        STC 6,C          START DMA1 READING TAPE.
      16155 102306        SFS 6
      16156 026155        JMP *-1          WAIT UNTIL DMA1 HAS FINISHED.
      16157 000000  CHECK NOP              ROUTINE TO CHECK PARITY.
```

Figure B-4. ADC3 Program

```
16160 102511        LIA 11B       LOAD TAPE STATUS WORD.
16161 012216        AND MASK1     PARITY BIT MASK.
16162 002002        SZA           SKIP IF (A) = 0.(PARITY OK)
16163 026167        JMP ERROR     BAD PARITY.
16164 000000        NOP           PARITY OK. (A)=177777 OCTAL.
16165 006400        CLB
16166 026112        JMP HALT:-1
16167 000000  ERROR NOP           PARITY CHECK-COMPUTER WILL
16170 062222        LDA THREE     STOP WITH 070707(OCTAL) IN (A).
16171 006004        INB           INCREMENT THE B REGISTER.
16172 102006        HLT 6         PARITY ERROR HALT.
16173 126167        JMP ERROR,I   CONTINUE.
16174 000000  REWND NOP           TAPE REWIND ROUTINE.
16175 102311        SFS 11B
16176 026175        JMP *-1
16177 062217        LDA REW
16200 103611        OTA 11B,C
16201 102311        SFS 11B
16202 026201        JMP *-1
16203 106700        CLC 0
16204 062223        LDA FOUR      (A) = 111111 OCTAL.
16205 102006  LAST  HLT 6
16206 026102        JMP BEGIN
16207 000000  COUNT NOP
16210 000003  CW1   OCT 3
16211 000041  CW2   OCT 41
16212 120010  DMA1  OCT 120010    READ TAPE CONTROL WORD.
16213 102000  ADDRS OCT 102000    MEMORY INPUT-ADDRESS=2000 OCTAL.
16214 174000  WORDS DEC -2048     NO. WORDS PER RECORD=2048.
16215 000023  TAPE  OCT 23        TAPE CONTROL WORD.
16216 000002  MASK1 OCT 2         PARITY BIT MASK WORD.
16217 000201  REW   OCT 201
16220 177777  ONE   OCT 177777
16221 000007  TWO   OCT 000007
16222 070707  THREE OCT 070707
16223 111111  FOUR  OCT 111111
                    END
**  NO ERRORS*
```

Figure B-4. ADC3 Program (continued)

```
                    ASMB,B,A,L,C
      00100                ORG 100B      PROGRAM STARTS AT 100 OCTAL.
*    FIRST OPERATION IS TO CHECK FOR LEGAL LABELED TAPE.
*
      00100 060456         LDA  HDCON       LOAD FIRST CONTROL WORD.
      00101 102606         OTA 6            TYPE OF OPERATION AND UNIT USE
      00102 106702         CLC 2            PREPARE FOR SECOND CONTROL WOR
      00103 060455         LDA HDAD         SECOND CONTROL WORD.
      00104 102602         OTA 2            INPUT ADDRESS IN CORE FOR FIRS
      00105 102702         STC 2            PREPARE--
      00106 060454         LDA HDLEN        LENGTH OF DATA FIELD TO BE REA
      00107 102602         OTA 2
      00110 060457         LDA READ         LOAD READ COMMANC FOR MAG. TAP
      00111 103611         OTA 11B,C        START TAPE DECK.
      00112 103706         STC 6,C          START THE DMA CHANNEL # 2.
      00113 102311         SFS 11B          WAIT FOR TAPE DECK.
      00114 024113         JMP *-1
      00115 060460         LDA VO           LOAD "VO" FROM 360 HEADER VOL1
      00116 020700         XOR 700B         CHECK FIRST DATA WORD.
      00117 002002         SZA
      00120 024405         JMP DEAD         FIRST WORD DID NOT COPARE--FOR
      00121 060461         LDA L1           LOAD "L1" FROM 360 HEADER RECO
      00122 020701         XOR 701B
      00123 002002         SZA              CHECK SECOND DATA WORD.
      00124 024405         JMP DEAD
      00125 014410         JSB FWDSP        SKIP SECOND FILE
      00126 014410         JSB FWDSP        SKIP THIRD FILE.
      00127 014410         JSB FWDSP        CHECK FOURTH FILE FOR TAPE MAR
      00130 034000         ISZ 0
      00131 024405         JMP DEAD         TAPE MARK NOT HERE AS SHOULD B
*
*
*
*     DATACON-CONVERT PROGRAM
*        DATA READ FROM ANALOG TO DIGITIAL CONVERTER
*        IS OUTPUTTED ON TAPE IN IBM 360/50 FORTRAN
*        FLOATING WORD FORMAT.  MAGNITUDE OF OUTPUT
*        IS LESS THAN ONE.
*           MAXIMUM DATA INPUT RATE IS 13 KILOWORDS PER SECOND
*
*
      00132 000000  START NOP
      00133 102000        HLT
      00134 000000        NOP             LOAD SW'S WITH NO. RECORDS.
      00135 102501        LIA 1
      00136 003004        CMA,INA          GENERATE TWOS COMPLEMENT
      00137 070462        STA REC         STORE 2'S COMPL IN REC.
      00140 000000  ENTER NOP
      00141 102000        HLT
      00142 000000        NOP             PUSH RUN WHEN READY TO START PGM
      00143 060462        LDA REC
      00144 070463        STA CNT         INI IALIZE RECORD COUNT.
      00145 106700        CLC 0           TURN OFF ALL I/O.
      00146 002400        CLA             CLEAR A FOR ERROR COUNT
      00147 070451        STA NER         SET ERROR COUNTER
      00150 103100        CLF 0           TURN INTERRUPT OFF.
      00151 060436  FIRST LDA CNTL1       INITIALIZE DMA1 TO READ ADC.
```

Figure B-5 ADC4 Program

```
00152 102606        OTA 6        CONTROL WORD ONE.
00153 106702        CLC 2
00154 060445        LDA ADR1
00155 102602        OTA 2        CONTROL WORD 2.
00156 102702        STC 2
00157 060437        LDA NBUF     NBUF IS "WORDS PER RECORD".
00160 102602        OTA 2        CONTROL WORD 3.
00161 103714        STC 14B,C    START ADC.
00162 103706        STC 6,C      START DMA1.
00163 060436  LOOP  LDA CNTL1    INITIALIZE DMA2 TO READ ADC.
00164 102607        OTA 7         CW1
00165 106703        CLC 3
00166 060446        LDA ADR2
00167 102603        OTA 3        CW2
00170 102703        STC 3
00171 060437        LDA NBUF
00172 102603        OTA 3        CW3
00173 102206        SFC 6        SKIP FLAG CLEAR-SKIP DMA1 BUSY.
00174 102006        HLT 6        ERROR HALT.
00175 102306        SFS 6        SKIP FLAG SET-SKIP WHEN DMA1 RDY
00176 024175        JMP *-1        WAIT FOR DMA1.
00177 000000        NOP
00200 103714        STC 14B,C
00201 103707        STC 7,C      START ADC & START DMA2.
00202 060444  THIRD LDA CNTL2    INITIALIZE DMA1 TO WRITE TAPE.
00203 102606        OTA 6
00204 106702        CLC 2
00205 060440        LDA RADR1
00206 102602        OTA 2        CW2
00207 102702        STC 2
00210 060442        LDA NBUFF
00211 102602        OTA 2        CW3
00212 060437        LDA NBUF    LOAD COMPLEMENT OF NUMBER OF RECOR
00213 070433        STA COUNT   SAVE COUNTER
00214 064447        LDB ADR10   STARTING ADDRESS OF A-D BUFFER
00215 074434        STB NUM
00216 044437        ADB NBUF    BACK UP FOR OUTPUT POINTER
00217 060443        LDA OUT     LOAD MAG TAPE "WRITE" COMMAND
00220 000040        CLE
00221 102311        SFS 11B      SKIP FLAG SET-SKIP WHEN TAPE RDY
00222 024221        JMP *-1      WAIT UNTIL TAPE IS READY.
00223 103611        OTA 11B,C    OUTPUT COMMAND WORD TO TAPE.
00224 103706        STC 6,C      START DMA1 TO TAPE.
00225 014362        JSB CONVT    START CONVERTING NUMBERS
00226 102306        SFS 6        SKIP FLAG SET-SKIP IF DMA1 FIN.
00227 024226        JMP *-1      WAIT UNTIL DMA1 IS FINISHED.
00230 102511        LIA 11B      GET TAPE STATUS WORD.
00231 010452        AND MASK1    CHECK PARITY STATE.
00232 002002        SZA          SKIP IF PARITY IS OK.
00233 014341        JSB ERROR    GO TO ERROR ROUTINE-BAD PARITY.
00234 034463        ISZ CNT      INCREMENT RECORD COUNT.
00235 024251        JMP FOUR
00236 060467        LDA JOB1     HALT ON RECORDS COMPLETE WITH
00237 064451        LDB NER       LOAD NUMBER OF ERRORS
00240 102006        HLT 6        (A) REGISTER = 70707*******
00241 014352        JSB ENDFL    PUSH START TO GET EOF MARK*****
00242 014424        JSB VOLEN      SUBROUTINE TO END VOLUME.
```

Figure B-5. ADC4 Program (continued)

```
00243 014344        JSB REWND    TAPE REWIND ROUTINE.
00244 106700        CLC 0        TURN OFF ALL I/O UNITS.
00245 064451        LDB NER      LOAD ERROR COUNT
00246 060470        LDA JOB2     HALT ON NORMAL JOB COMPLETE----
00247 102006        HLT 6        LOAD A NEW REEL OF TAPE AND PUSH
00250 024405        JMP DEAD     RUN TO REPEAT ENTIRE PROGRAM.
00251 060436  FOUR  LDA CNTL1    INITIALIZE DMA1 TO READ ADC.
00252 102606        OTA 6
00253 106702        CLC 2
00254 060445        LDA ADR1
00255 102602        OTA 2        CW2
00256 102702        STC 2
00257 060437        LDA NBUF
00260 102602        OTA 2        CW3
00261 102207        SFC 7        SKIP IF DMA2 IS BUSY.
00262 102007        HLT 7        ERROR HALT.
00263 102307        SFS 7        SKIP IF BUFFER2 IS FULL.
00264 024263        JMP *-1      WAIT UNTIL DMA2 FLAG IS SET.
00265 103714        STC 14B,C    START ADC.
00266 103706        STC 6,C      START DMA1.
00267 060444        LDA CNTL2    INITIALIZE DMA2 TO WRITE TAPE.
00270 102607        OTA 7        CW1
00271 1067[illegible]        CLC 3
00272 060441        LDA RADR2
00273 102603        OTA 3        CW2
00274 102703        STC 3
00275 060442        LDA NBUFF
00276 102603        OTA 3        CW3
00277 060437        LDA NBUF     LOAD COMPLEMENT OF NUMBER OF RECO
00300 070433        STA COUNT    SAVE IN COUNTER
00301 064450        LDB ADR20    STARTING ADDRESS OF A-D BUFFER
00302 074434        STB NUM      STORE ADDRESS--INPUT POINTER
00303 044437        ADB NBUF     BACK UP THE OUTPUT POINTER
00304 060443        LDA OUT      LOAD MAG TAPE "WRITE" COMMAND
00305 000040        CLE
00306 102311        SFS 11B      SKIP WHEN TAPE IS READY.
00307 024306        JMP *-1      WAIT UNTIL TAPE IS READY.
00310 103611        OTA 11B,C    START TAPE MACHINE.
00311 103707        STC 7,C      START DMA2 TO TAPE.
00312 014362        JSB CONVT    START CONVERTING NUMBERS
00313 102307        SFS 7        SKIP WHEN DMA2 IS FINISHED.
00314 024313        JMP *-1      WAIT UNTIL DMA2 IS FINISHED.
00315 102511        LIA 11B      GET TAPE STATUS WORD.
00316 010452        AND MASK1    CHECK PARITY STATE.
00317 002002        SZA          SKIP IF PARITY IS OK.
00320 014341        JSB ERROR    BAD PARITY.
00321 034463        ISZ CNT      INCREMENT RECORD COUNT.
00322 024163        JMP LOOP
00323 060467        LDA JOB1
00324 064451        LDB NER      LOAD NUMBER OF ERRORS
00325 102007        HLT 7        RECORDS COMPLETE. PUSH RUN TO
00326 000000        NOP          WRITE EOF AND REWIND TAPE.
00327 014352        JSB ENDFL    GO TO END-OF-FILE ROUTINE.
00330 014424        JSB VOLEN      END VOLUME OR START MULTIPLE DA
00331 014344        JSB REWND    GO TO REWIND ROUTINE.
00332 000000        NOP
00333 106700        CLC 0        TURN OFF ALL I/O UNITS.
```

Figure B-5   ADC4 Program (continued)

```
00334 060470        LDA JOB2
00335 064451        LDB NER        LOAD NUMBER OF ERRORS
00336 102007        HLT 7          PUSH REN TO REPEAT ENTIRE PGM.
00337 024405  FIVE  JMP DEAD
00340 024163        JMP LOOP       GO READ ANOTHER RECORD.
00341 000000  ERROR NOP            PARITY ERROR ROUTINE.
00342 034451        ISZ NER        UPDATE THE ERROR COUNT
00343 124341        JMP ERROR,I    RETURN TO MAIN PROGRAM.
00344 000000  REWND NOP            REWIND ROUTINE.
00345 102311        SFS 11B        SKIP WHEN TAPE IS READY.
00346 024345        JMP *-1        WAIT UNTIL TAPE IS READY.
00347 060453        LDA REW        GET REWIND COMMAND WORD.
00350 103611        OTA 11B,C      REWIND TAPE.
00351 124344        JMP REWND,I    RETURN TO MAIN PROGRAM.
00352 000000  ENDFL NOP            END-OF-FILE ROUTINE.
00353 102311        SFS 11B        SKIP WHEN TAPE IS READY.
00354 024353        JMP *-1
00355 060435        LDA FILE       GET TAPE EOF COMMAND WORD.
00356 103611        OTA 11B,C      WRITE E-O-F.
00357 102311        SFS 11B
00360 024357        JMP *-1        WAIT UNTIL TAPE IS READY.
00361 124352        JMP ENDFL,I    RETURN TO MAIN PROGRAM.
00362 000000  CONVT NOP            SPACE FOR SUBROUTINE RETURN ADDRE
00363 160434  STTT  LDA NUM,I       LOAD NUMBER TO BE CONVERTED
00364 010465        AND MSKK       DROP LEAST SIGNFICANT FIGURES(TWO
00365 001623        ELA,RAR        SAVE SIGN IN E REGISTURE
00366 002204        CME,INA        CORRECT SIGN-SET EXPONENT SIGN
00367 001325        RAR,ERA        MOVE IN BOTH SIGN BITS
00370 170001        STA 1,I        STORE IN ADDRESS GIVEN IN B REGIS
00371 006004        INB            UPDATE THE OUTPUT ADDRESS
00372 160434        LDA NUM,I      LOAD NUMBER AGAIN
00373 010466        AND MSKL       DROP ALL BUT LEAST TWO SIGNFICANT
00374 001323        RAR,RAR        ROTATE AROUND TO THE HIGH ORDER E
00375 170001        STA 1,I
00376 006104        CLE,INB        UPDATE THE OUTPUT ADDRESS
00377 034434        ISZ NUM        UPDATE THE INPUT ADDRESS
00400 034433        ISZ COUNT      UPDATE THE COUNTER,SKIP IF END
00401 024363        JMP STTT
00402 102211        SFC 11B         CHECK TO BE SURE TAPE DIDN'T GET
00403 102066        HLT 66B
00404 124362        JMP CONVT,I    BRANCH BACK TO MAIN PROGRAM.
*
*     DEAD SUBROUTINE--HEADER LABEL NOT ACCEPTABLE.
*           TAPE IS REWOUND AND MAG TAPE UNIT RETURNED TO LOCAL.
*
00405 014344  DEAD  JSB REWND          REWIND AN STANDBY.
00406 102025        HLT 25B            STOP FOR OPERATOR ACTION
00407 024100        JMP 100B           RETURN TO START OF PROGRAM
*   THE OPERATOR IS EXPECTED TO SUPPLY A NEW REEL OF TAPE--
*   A LABELED ONE BEFORE PUSHING "RUN".
*
****************
*
*     SUBROUTINE TO FORWARD SPACE RECORD ON MAG TAPE UNIT
*
00410 000000  FWDSP NOP            RETURN ADDRESS OR SUBROUTINE EXIT
00411 060422        LDA FWD        LOAD FORWARD SPACE RECORD COMMAND
```

Figure B-5. ADC4 Program (continued)

```
00412 103611        OTA 11B,C     OUTPUT COMMAND
00413 102311        SFS        11B    SKIP WHEN TAPE UNIT COMPLETED
00414 024413        JMP *-1       WAIT FOR COMPLETION OF OPERATION
00415 102511        LIA 11B       LOAD STATUS WORD
00416 010423        AND CWORD
00417 002002        SZA           CHECK FOR TAPE MARK
00420 003400        CCA           SET "A" TO -1 IF TAPE MARK SENSED
00421 124410        JMP FWDSP,I   RETURN TO MAIN PROGRAM.
00422 000003  FWD   OCT 3         TAPE COMMAND--FORWARD SPACE RECOR
00423 000200  CWORD OCT 200       MASK FOR SENSING WHEN TAPE MARK P
*
*      UPON RETURN--  "A" IS 0 IF NO TPE MARK SENSED.
*                     "A" IS -1 IS TAPE MARK DETECTED
*
*
*
*     SUBROUTINE      ALLOWS OPTION OF ENDING VOLUME OR
*                     CONTINUE LOADING DATA UNDER MULTIPLE
*                     DATA SET IBM 360 OPTION.
*
*
00424 000000  VOLEN NOP          SAVE RETURN ADDRESS AREA
00425 102070        HLT 70B      HALT FOR OPERATOR RESPONSE
00426 102501        LIA 1         LOAD SWITCH REGISTURE.
00427 002020        SSA          CHECK OPERATORS INSTRUCTION
00430 0241 ?        JMP START    PREPARE TO LOAD DATA SET--MULTIPLE
00431 014352        JSB ENDFL    PLACE SECOND FILE MARK--VOLUME END
00432 124424        JMP VOLEN,I RETURN TO MAIN PROGRAM.
00433 000000  COUNT OCT 0         COUNTER IN CONVERT ROUTINE
00434 000000  NUM   OCT 0         INPUT POINTER IN CONVERT ROUTINE
00435 000035  FILE  OCT 35        E-O-F COMMAND WORD.
00436 100014  CNTL1  OCT 100014   CONTROL WORD--NO "CLC" AT END OF
00437 174150  NBUF   DEC -1944   BUFFER LENGTH.
00440 000500  RADR1 OCT 500          TAPE OUTPUT BUFFER #1.
00441 010200  RADR2 OCT 10200        TAPE OUTPUT BUFFER #2.
00442 170314  NBUFF DEC -3892
00443 000031  OUT   OCT 31        TAPE WRITE COMMAND WORD.
00444 160010  CNTL2 OCT 160010    CONTRCL WORD NO. 2 FOR DMA.
00445 104334  ADR1  OCT 104334
00446 114034  ADR2  OCT 114034
00447 004334  ADR10 OCT 4334
00450 014034  ADR20 OCT 14034
00451 000000  NFR   OCT 0          STORAGE FOR NUMBER OF PARITY ERRO
00452 000002  MASK1 OCT 2          MASK TO CHECK PARITY ON TAPE.
00453 000101  REW   OCT 101       TAPE COMMAND--REWIND AND STAND BY
00454 177660  HDLEN OCT -120     HEADER LENGTH
00455 100700  HDAD OCT 100700  LOAD DATA TO CORE 700B UP.
00456 160010  HDCON OCT 160010  DMA CONTROL--USE UNIT 10
00457 000023  READ  OCT 23        MAG TAPE COMMAND TO READ.
00460 162726  VO    OCT 162726
00461 151761  L1    OCT 151761
00462 000000  REC   NOP            ENTER NUMBER OF RECORDS HERE.
00463 000000  CNT   NOP            PUT 2'S COMPLEMENT OF RECORDS H
00464 000035  FL    OCT 35         TAPE E-O-F COMMAND WORD.
00465 177774  MSKK  OCT 177774     MASK TO DROP LEAST TWO SIGNIFICAN
00466 000003  MSKL  OCT 3          MASK TO DROP ALL BUT LEAST TWO SI
00467 077777  JOB1  OCT 77777      LOADED INTO "A" WHEN RECORDS HAVE
```

Figure B-5   ADC4 Program (continued)

```
      00470 070707  JOB2  OCT 70707     LOADED INTO "A" --END OF JOB
*
*   SET UP INITIAL CONSTANTS FOR FORTRAN TAPE FORMAT
      00500                 ORG 500B
      00500 017150          DEC 7784
      00501 000000          OCT 0
      00502 017144          DEC 7760
      00503 000000          OCT 0
*
      10200                 ORG 10200B      START TO SET UP CONSTANTS.
      10200 017150          DEC 7784    BYTE LENGTH OF BLOCK
      10201 000000          OCT 0           CONTROL WORD
      10202 017144          DEC 7780    BYTE LENGTH OF LRECL
      10203 000000          OCT 0           CONTROL WORD.
*
*
*          THIS IS NECESSARY SINCE FORTRAN WILL NOT ACCEPT
*          CORE TYPE DUMPS.  ALL RECORDS MUST BE HEADED
*          WITH RECORD LENGTH AND BLOCK LENGTHS WHERE APPLICABLE
*
*  HALT 66(OCTAL) MEANS TAPE DRIVE LOADED NUMBERS FASTER THAN
*         THE CONVERT PROGRAM WAS ABLE TO CONVERT THE OUTPUT
*         DATA--THIS SHOULD NEVER HAPPEN
*
*  HALT 6 AND 7 ARE ERROR HALTS UNLESS "A" REGISTURE IS LOADED
*         WITH JOB1 OR JOB2 -- OPERATOR CORRECTION IS TO SLOW
*         DOWN THE INPUT RATE OF DATA--MAXIMUM RATE IS
*         APPROXIMATELY 13,000 WORDS PER SECOND.
                            END 77B
** NO ERRORS*
```

Figure B-5 ADC4 Program (continued)

```
                    ASMB,B,L,A,C,T
      00100               ORG 100B       PROGRAM STARTS AT 100 OCTAL.
*
*
*
*     DATACON-CONVERT PROGRAM
*        DATA READ FROM ANALOG TO DIGITIAL CONVERTER
*        IS OUTPUTTED ON TAPE IN IBM 360/50 FORTRAN
*        FLOATING WORD FORMAT.  MAGNITUDE OF OUTPUT
*        IS LESS THAN ONE.
*           MAXIMUM DATA INPUT RATE IS 13 KILOWORDS PER SECOND
*
*
      00100 000000  BEGIN NOP
      00101 060402        LDA FILE       LOAD COMMAND WORD FOR FILE MARK.
      00102 102611        OTA 11B
      00103 000000  START NOP
      00104 102000        HLT
      00105 000000        NOP            LOAD SW'S WITH NO. RECORDS.
      00106 102501        LIA 1
      00107 003004        CMA,INA         GENERATE TWOS COMPLEMENT
      00110 070421        STA REC        STORE 2'S COMPL IN REC.
      00111 102001  ENTER HLT 1          PUSH RUN TO START LOADING DATA.
      00112 000000        NOP            PUSH RUN WHEN READY TO START PGM
      00113 060421        LDA REC
      00114 070422        STA CNT        INITIALIZE RECORD COUNT.
      00115 106700        CLC 0          TURN OFF ALL I/O.
      00116 002400        CLA            CLEAR A FOR ERROR COUNT
      00117 070416        STA NER        SET ERROR COUNTER
      00120 103100        CLF 0          TURN INTERRUPT OFF.
      00121 060403  FIRST LDA CNTL1      INITIALIZE DMA1 TO READ ADC
      00122 102606        OTA 6          CONTROL WORD ONE.
      00123 106702        CLC 2
      00124 060412        LDA ADR1
      00125 102602        OTA 2          CONTROL WORD 2.
      00126 102702        STC 2
      00127 060404        LDA NBUF       NBUF IS "WORDS PER RECORD".
      00130 102602        OTA 2          CONTROL WORD 3.
      00131 103714        STC 14B,C      START ADC.
      00132 103706        STC 6,C        START DMA1.
      00133 060403  LOOP  LDA CNTL1      INITIALIZE DMA2 TO READ ADC.
      00134 102607        OTA 7           CW1
      00135 106703        CLC 3
      00136 060413        LDA ADR2
      00137 102603        OTA 3          CW2
      00140 102703        STC 3
      00141 060404        LDA NBUF
      00142 102603        OTA 3          CW3
      00143 102206        SFC 6          SKIP FLAG CLEAR-SKIP DMA1 BUSY.
      00144 102006        HLT 6          ERROR HALT.
      00145 102306        SFS 6          SKIP FLAG SET-SKIP WHEN DMA1 RDY
      00146 024145        JMP *-1        WAIT UNTIL DMA1 IS FINISHED.
      00147 000000        NOP
      00150 103714        STC 14B,C
      00151 103707        STC 7,C        START ADC & START DMA2.
      00152 061411  THIRD LDA CNTL2      INITIALIZE DMA1 TO WRITE TAPE.
      00153 102606        OTA 6
```

Figure B-6. ADC5 Program

```
00154 106702          CLC 2
00155 060405          LDA RADR1
00156 102602          OTA 2        CW2
00157 102702          STC 2
00160 060407          LDA NBUFF
00161 102602          OTA 2        CW3
00162 060404          LDA NBUF    LOAD COMPLEMENT OF NUMBER OF RECOR
00163 070400          STA COUNT   SAVE COUNTER
00164 064414          LDB ADR1    STARTING ADDRESS OF A-D BUFFER
00165 074411          STB NUM
00166 044404          ADB NBUF    BACK UP FOR OUTPUT POINTER
00167 060410          LDA OUT     LOAD MAG TAPE "WRITE" COMMAND
00170 000040          CLE
00171 102311          SFS 11B      SKIP FLAG SET-SKIP WHEN TAPE RDY
00172 024171          JMP *-1      WAIT UNTIL TAPE IS READY.
00173 103611          OTA 11B,C    OUTPUT COMMAND WORD TO TAPE.
00174 103706          STC 6,C      START DMA1 TO TAPE.
00175 014346          JSB CONVT    START CONVERTING NUMBERS
00176 102306          SFS 6        SKIP FLAG SET-SKIP IF DMA1 FIN.
00177 024176          JMP *-1      WAIT UNTIL DMA1 IS FINISHED.
00200 102511          LIA 11B      GET TAPE STATUS WORD.
00201 010417          AND MASK1    CHECK PARITY STATE.
00202 002002          SZA          SKIP IF PARITY IS OK.
00203 014303          JSB ERROR    GO TO ERROR ROUTINE-BAD PARITY.
00204 034402          ISZ CNT      INCREMENT RECORD COUNT.
00205 024226          JMP FOUR
00206 060425          LDA JOB1     HALT ON RECORDS COMPLETE WITH
00207 064416          LDB NER       LOAD NUMBER OF ERRORS
00210 102306          SFS 6        WAIT FOR TAPE DECK TO FINISH.
00211 024210          JMP *-1
00212 106700          CLC 0        CLEAR ALL I/O
00213 102066          HLT 66B      HALT FOR OPERATOR ACTION.
00214 014336          JSB ENDFL    PUSH START TO GET EOF MARK*****
00215 014371          JSB VOLEN      SUBROUTINE TO END VOLUME.
00216 014326          JSB REWND    TAPE REWIND ROUTINE.
00217 106700          CLC 0        TURN OFF ALL I/O UNITS.
00220 064416          LDB NER      LOAD ERROR COUNT
00221 060426          LDA JOB2     HALT ON NORMAL JOB COMPLETE----
00222 102006          HLT 6        LOAD A NEW REEL OF TAPE AND PUSH
00223 000000          NOP          RUN TO REPEAT ENTIRE PROGRAM.
00224 024100          JMP BEGIN    ******************************
00225 000000          NOP          ******************************
00226 060403    FOUR  LDA CNTL1    INITIALIZE DMA1 TO READ ADC.
00227 102606          OTA 6
00230 106702          CLC 2
00231 060412          LDA ADR1
00232 102602          OTA 2        CW2
00233 102702          STC 2
00234 060404          LDA NBUF
00235 102602          OTA 2        CW3
00236 102207          SFC 7        SKIP IF DMA2 IS BUSY.
00237 102007          HLT 7        ERROR HALT.
00240 102307          SFS 7        SKIP IF BUFFER2 IS FULL.
00241 024240          JMP *-1      WAIT UNTIL DMA2 FLAG IS SET.
00242 103714          STC 14B,C    START ADC.
00243 103706          STC 6,C      START DMA1.
00244 060411          LDA CNTL2    INITIALIZE DMA2 TO WRITE TAPE.
```

Figure B-6. ADC5 Program (continued)

```
00245 102607         OTA 7        CW1
00246 106703         CLC 3
00247 060406         LDA RADR2
00250 102603         OTA 3        CW2
00251 102703         STC 3
00252 060437         LDA NBUFF
00253 102603         OTA 3        CW3
00254 060404         LDA NBUF     LOAD COMPLEMENT OF NUMBER OF RECO
00255 070400         STA COUNT    SAVE IN COUNTER
00256 064415         LDB ADR20    STARTING ADDRESS OF A-D BUFFER
00257 074401         STB NUM      STORE ADDRESS--INPUT POINTER
00260 044404         ADB NBUF     BACK UP THE OUTPUT POINTER
00261 060410         LDA OUT      LOAD MAG TAPE "WRITE" COMMAND
00262 000040         CLE
00263 102311         SFS 11B      SKIP WHEN TAPE IS READY.
00264 024263         JMP *-1      WAIT UNTIL TAPE IS READY.
00265 103611         OTA 11B,C    START TAPE MACHINE.
00266 103707         STC 7,C      START DMA2 TO TAPE.
00267 014346         JSB CONVT    START CONVERTING NUMBERS
00270 102307         SFS 7        SKIP WHEN DMA2 IS FINISHED.
00271 024270         JMP *-1      WAIT UNTIL DMA2 IS FINISHED.
00272 102511         LIA 11B      GET TAPE STATUS WORD.
00273 010417         AND MASK1    CHECK PARITY STATE.
00274 002002         SZA          SKIP IF PARITY IS OK.
00275 014323         JSB ERROR    BAD PARITY.
00276 034422         ISZ CNT      INCREMENT RECORD COUNT.
00277 024133         JMP LOOP
00300 060425         LDA JOB1
00301 064416         LDB NER      LOAD NUMBER OF ERRORS
00302 102307         SFS 7        WAIT FOR TAPE DECK TO FINISH.
00303 024302         JMP *-1
00304 106700         CLC 0        CLEAR ALL I/O DEVICES.
00305 102077         HLT 77B      RECORDS COMPLETE.  PUSH RUN TO
00306 000000         NOP          WRITE EOF AND REWIND TAPE.
00307 014336         JSB ENDFL    GO TO END-OF-FILE ROUTINE.
00310 014371         JSB VOLEN      END VOLUME OR START MULTIPLE DA
00311 014326         JSB REWND    GO TO REWIND ROUTINE.
00312 000000         NOP
00313 106700         CLC 0        TURN OFF ALL I/O UNITS.
00314 060426         LDA JOB2
00315 064416         LDB NER      LOAD NUMBER OF ERRORS
00316 102007         HLT 7        PUSH REN TO REPEAT ENTIRE PGM.
00317 000000         NOP          LOAD NEW TAPE*****************
00320 000000         NOP          ******************************
00321 024100   FIVE  JMP BEGIN    ******************************
00322 024133         JMP LOOP     GO READ ANOTHER RECORD.
00323 000000   ERROR NOP          PARITY ERROR ROUTINE.
00324 034416         ISZ NER      UPDATE THE ERROR COUNT
00325 124323         JMP ERROR,I  RETURN TO MAIN PROGRAM.
00326 000000   REWND NOP          REWIND ROUTINE.
00327 102311         SFS 11B      SKIP WHEN TAPE IS READY.
00330 024327         JMP *-1      WAIT UNTIL TAPE IS READY.
00331 060420         LDA REW      GET REWIND COMMAND WORD.
00332 103611         OTA 11B,C    REWIND TAPE.
00333 102311         SFS 11B      SKIP WHEN TAPE IS REWOUND.
00334 024333         JMP *-1
00335 124326         JMP REWND,I  RETURN TO MAIN PROGRAM.
```

Figure B-6. ADC5 Program (continued)

```
00336 000000 ENDFL NOP            END-OF-FILE ROUTINE.
00337 102311       SFS 11B        SKIP WHEN TAPE IS READY.
00340 024337       JMP *-1
00341 060402       LDA FILE       GET TAPE EOF COMMAND WORD.
00342 103611       OTA 11B,C      WRITE E-O-F.
00343 102311       SFS 11B
00344 024343       JMP *-1        WAIT UNTIL TAPE IS READY.
00345 124336       JMP ENDFL,I    RETURN TO MAIN PROGRAM.
00346 000000 CONVT NOP            SPACE FOR SUBROUTINE RETURN ADDRE
00347 160401 STTT  LDA NUM,I       LOAD NUMBER TO BE CONVERTED
00350 010423       AND MSKK       DROP LEAST SIGNFICANT FIGURES(TWO
00351 001623       ELA,RAR        SAVE SIGN IN E REGISTURE
00352 002204       CME,INA        CORRECT SIGN-SET EXPONENT SIGN
00353 001325       RAR,ERA        MOVE IN BOTH SIGN BITS
00354 170001       STA 1,I        STORE IN ADDRESS GIVEN IN B REGIS
00355 006004       INB            UPDATE THE OUTPUT ADDRESS
00356 160401       LDA NUM,I      LOAD NUMBER AGAIN
00357 010424       AND MSKL       DROP ALL BUT LEAST TWO SIGNFICANT
00360 001323       RAR,RAR        ROTATE AROUND TO THE HIGH ORDER E
00361 170001       STA 1,I
00362 006104       CLE,INB        UPDATE THE OUTPUT ADDRESS
00363 034401       ISZ NUM        UPDATE THE INPUT ADDRESS
00364 034400       ISZ COUNT      UPDATE THE COUNTER,SKIP IF END
00365 024347       JMP STTT
00366 102211       SFC 11B         CHECK TO BE SURE TAPE DIDN'T GET
00367 102052       HLT 52B        ERROR HALT--SERIOUS---.
00370 124346       JMP CONVT,I    BRANCH BACK TO MAIN PROGRAM.
*
*
*      SUBROUTINE      ALLOWS OPTION OF ENDING VOLUME OR
*                      CONTINUE LOADING DATA UNDER MULTIPLE
*                      DATA SET IBM 360 OPTION.
*
*
00371 000000 VOLEN NOP           SAVE RETURN ADDRESS AREA
00372 102070       HLT 70B       HALT FOR OPERATOR RESPONSE
00373 060001       LDA 1         LOAD SWITCH REGISTURE
00374 002020       SSA           CHECK OPERATORS INSTRUCTION
00375 024103       JMP START     PREPARE TO LOAD DATA SET--MULTIPLE
00376 014336       JSB ENDFL     PLACE SECOND FILE MARK--VOLUME END
00377 124371       JMP VOLEN,I RETURN TO MAIN PROGRAM.
00400 000000 COUNT OCT 0          COUNTER IN CONVERT ROUTINE
00401 000000 NUM   OCT 0          INPUT POINTER IN CONVERT ROUTINE
00402 000035 FILE  OCT 35        E-O-F COMMAND WORD.
00403 120014 CNTL1 OCT 120014    CONTROL WORD NO. 1 FOR DMA.
00404 174142 NBUF  DEC -1950         SHORT BUFFER LENGTH
00405 000500 RADR1 OCT 500           TAPE OUTPUT BUFFER #1.
00406 010200 RADR2 OCT 10200         TAPE OUTPUT BUFFER #2.
00407 170300 NBUFF DEC -3904         LENGTH OF TAPE BUFFER.
00410 000031 OUT   OCT 31        TAPE WRITE COMMAND WORD.
00411 160010 CNTL2 OCT 160010    CONTROL WORD NO. 2 FOR DMA.
00412 104342 ADR1  OCT 104342        A-D INPUT BUFFER #1.
00413 114342 AD22  OCT 114342        A-D INPUT BUFFER #2.
00414 004342 ADR10 OCT 004342        SHORT BUFFER #1.
00415 014342 AD220 OCT 014342        SHORT BUFFER #2.
00416 000000 NER   OCT 0          STORAGE FOR NUMBER OF PARITY ERRO
00417 000002 MASK1 OCT 2          MASK TO CHECK PARITY ON TAPE.
```

Figure B-6. ADC5 Program (continued)

```
00420 000201  REW    OCT 201       TAPE REWIND COMMAND WORD.
00421 000000  REC    NOP           ENTER NUMBER OF RECORDS HERE.
00422 000000  CNT    NOP           PUT 2'S COMPLEMENT OF RECORDS H
00423 177774  MSKK   OCT 177774    MASK TO DROP LEAST TWO SIGNIFICAN
00424 000003  MSKL   OCT 3         MASK TO DROF ALL BUT LEAST TWO SI
00425 077777  JOB1   OCT 77777     LOADED INTO "A" WHEN RECORDS HAVE
00426 070707  JOB2   OCT 70707     LOADED INTO "A" --END OF JOB
*
*   SET UP INITIAL CONSTANTS FOR FORTRAN TAPE FORMAT
00500                ORG 500B
00500 017200         DEC 7808
00501 000000         OCT 0
00502 017174         DEC 7804
00503 000000         OCT 0
*
10200                ORG 10200B        START TO SET UP CONSTANTS.
10200 017200         DEC 7808          BLKSIZE ENTRY.
10201 000000         OCT 0             CONTROL WORD
10202 017174         DEC 7804          LRECL SIZE.
10203 000000         OCT 0             CONTROL WORD.
*
*
*        THIS IS NECESSARY SINCE FORTRAN WILL NOT ACCEPT
*        CORE TYPE DUMPS.  ALL RECORDS MUST BE HEADED
*        WITH RECORD LENGTH AND BLOCK LENGTHS WHERE APPLICABLE
*
*  HALT 66(OCTAL) MEANS TAPE DRIVE LOADED NUMBERS FASTER THAN
*       THE CONVERT PROGRAM WAS ABLE TO CONVERT THE OUTPUT
*       DATA--THIS SHOULD NEVER HAPPEN
*
*  HALT 6 AND 7 ARE ERROR HALTS UNLESS "A" REGISTURE IS LOADED
*       WITH JOB1 OR JOB2 -- OPERATOR CORRECTION IS TO SLOW
*       DOWN THE INPUT RATE OF DATA--MAXIMUM RATE IS
*       APPROXIMATELY 13,000 WORDS PER SECOND.
                     END 77B
** NO ERRORS*
```

Figure B-6 ADC5 Program (continued)

```
                      ASMB,B,L,T,A,C
07000                       ORG 7000B
07000 102077          START HLT 77B       STOP FOR CONVENIENCE
07001 103714                STC 14B,C     START THE A-D CONVERTOR
07002 102314                SFS 14B       SKIP IF DATA READY
07003 027002                JMP *-1       WAIT FOR NEXT DATA WORD
07004 106514                LIB 14B       LOAD THE DATA WORD
07005 102501                LIA 1         PICK UP OPERATOR DATA WORD
07006 002020                SSA           IF 15 BIT IS UP -- STOP
07007 027000                JMP START     GO BACK AND STOP
07010 027002                JMP START+2 GO BACK AND WAIT FOR NEXT DATA WOR
                            END
**  NO ERRORS*
```

Figure B-7. DIAG1 Program

```
                    ASMB,B,L,A,T,C
00100                     ORG 100B
00100 102007              HLT 7       STOP FOR RECORD LENGTH
00101 102501              LIA 1       LOAD RECORD LENGTH
00102 003004              CMA,INA     GENERATE THE TWOS COMPLEMENT
00103 070147              STA CW3     SAVE THE RECORD LENGTH
00104 002400              CLA         CLEAR FOR RECORD COUNTER
00105 070155              STA SAVE    SAVE THE COUNTER
00106 060155        START LDA SAVE     LOAD THE RECORD COUNTER
00107 064155              LDB SAVE
00110 102076              HLT 76B
00111 002004              INA         UPDATE THE COUNTER
00112 070155              STA  SAVE   SAVE THE UPDATED COUNTER
*
*   INITIALIZE DATA STORAGE AREA
*
00113 060153              LDA BEGN      LOAD STARTING ADDRESS
00114 064150              LDB COUNT     LOAD COUNTER
00115 074151              STB TEMP      STORE COUNTER
00116 064152              LDB FILL      LOAD CLEARING WORD
00117 174000              STB 0,I       STORE CLEARING WORD IN ADDRESS IN
00120 002004              INA           GENERATE NEXT ADDRESS
00121 034151              ISZ TEMP      CHECK COUNTER
00122 024117              JMP *-3        KEEP GOING
00123 000000              NOP
00124 060145              LDA CW1       LOAD FIRST CONTROL WORD
00125 102606              OTA 6
00126 106702              CLC 2         PREPARE FOR SECOND CONTROL WORD
00127 060146              LDA CW2       LOAD SECOND CONTROL WORD
00130 102602              OTA 2
00131 102702              STC 2         PREPARE FOR THIRD CONTROL WORD
00132 060147              LDA CW3       LOAD THIRD CONTROL WORD
00133 102602              OTA 2
00134 060154              LDA READ      TELL MAG TAPE UNIT TO READ CHARAC
00135 103611              OTA 11B,C     START MAG TAPE UNIT
00136 103706              STC 6,C       START DMA CHANNEL 1
00137 102501        STAY  LIA 1       LOAD ADDRESS
00140 002020              SSA         CHECK FOR RETURN
00141 024106              JMP   START
00142 040153              ADA BEGN
00143 164000              LDB 0,I
00144 024137              JMP STAY   KEEP IN LOOP
00145 160010        CW1   OCT 160010    CONTROL WORD #1
*   SET CONTROL BIT ON I/O CHANNEL
*   USE BYTE MODE OF UNPACKING DATA
*   CLEAR CONTROL BIT IN I/O CHANNEL AT END DATA TRANSFER
00146 104000        CW2   OCT 104000    CONTROL WORD #2
*   INPUT DATA INTO LOCATION 4000 OCTAL
00147 170400        CW3   OCT -7400     EACH RECORD IS 7400 OCTAL IN LENG
00150 170300        COUNT OCT -7500     as large as 17700
00151 000000        TEMP  OCT 0
00152 102077        FILL  OCT 102077
00153 004000        BEGN  OCT 4000
00154 000023        READ  OCT 23        MAGNETIC TAPE COMMAND TO READ CHA
00155 000000        SAVE  OCT 0
00200                     ORG 200B          START AT NEW ORGIN
00200 060215              LDA FWD           LOAD COMMAND TO FORWARD SPACE
00201 103611              OTA 11B,C      OUTPUT COMMAND
```

Figure B-8. DIAG2 Program

```
00202 102311         SFS 11B        WAIT FOR MAG TAPE OPERATION
00203 024202         JMP *-1
*       CHECK TO SEE IF END OF FILE
00204 102511         LIA 11B
00205 010216         AND MSK
00206 002002         SZA
00207 024212         JMP AA
00210 002400         CLA               CLEAR A FOR INDICATOR
00211 024213         JMP *+2
00212 003400   AA    CCA               SET A FOR EOF MARK
00213 102000         HLT
00214 024200         JMP 200B
00215 000003   FWD   OCT 3          FORWARD SPACE RECORD COMMAND
00216 000200   MSK   OCT 200        BIT '7' IS SET FOR EOF MARK
                     END
** NO ERRORS*
```

Figure B-8. DIAG2 Program (continued)

```
                    ASMB,B,L,A,C
*
***** SUM NUMBERS FROM CHANNEL 14--USE TO SET OFFSET VOLTAGE.
*
      07000                ORG 7000B
      07000 102077         HLT 77B
      07001 102314  GO2    SFS 14B         WAIT FOR FLAG FROM A/D.
      07002 027001         JMP *-1
      07003 107514         LIB 14B,C
      07004 000040         CLE
      07005 005623         ELB,RBR
      07006 002041         SEZ,RSS
      07007 007004         CMB,INB
      07010 040001         ADA 1
      07011 106501         LIB 1
      07012 006020         SSB
      07013 002400         CLA
      07014 027001         JMP GO2
*
***** SAVE LARGEST VALUE FOR PEAK DETERMINATION.
*
      07100                ORG 7100B
      07100 102055         HLT 55B
      07101 102314  GO1    SFS 14B
      07102 027101         JMP *-1
      07103 107514         LIB 14B,C
      07104 000040         CLE
      07105 005623         ELB,RBR
      07106 077125         STB HOLD
      07107 007004         CMB,INB
      07110 047126         ADB LARGE
      07111 006021         SSB,RSS
      07112 027116         JMP GO3
      07113 067125         LDB HOLD
      07114 077126         STB LARGE
      07115 074000         STB 0
      07116 106501  GO3    LIB 1
      07117 006021         SSB,RSS
      07120 027101         JMP GO1
      07121 006400         CLB
      07122 077126         STB LARGE
      07123 074000         STB 0
      07124 027101         JMP GO1
      07125 000000  HOLD   OCT 0
      07126 000000  LARGE  OCT 0
                           END
** NO ERRORS*
```

Figure B-9. DIAG3 Program

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13. ABSTRACT

The Oklahoma State University Themis Weather Phenomena Project sampled severe storm sferics in the vicinity of central Oklahoma, at Black Hills, South Dakota; Greeley, Colorado and Las Cruces - White Sands, New Mexico

The doctoral dissertations have been written using Themis sferic data. The first paper derived a theory of computer learning in which the teacher is considered to be both perfect and another, more general case, where the teacher is imperfect. The second paper derived a theoretical computer model for describing various lightning strokes. The third paper describes the spectral power density content of the sampled sferics.

Sferic stroke rate is shown to strongly correlate with the rate of growth of a convective cell.

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